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PROCEEDINGS OF THE NATIONAL GROUND WATER QUALITY SYMPOSIUM, AUGUST 25-27, 1971, DENVER, COLORADO

National Water Well Association

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PROCEEDINGS
of the
NATIONAL GROUND WATER QUALITY SYMPOSIUM

Cosponsored by the
Environmental Protection Agency
and the
National Water Well Association ✓

August 25-27, 1971

Denver, Colorado

Dedicated to C. E. Jacob (1914-1970)

Contract No. 68-01-0004
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FOREWORD

THE OBJECTIVE

by Jay H. Lehr[a]

During the past decade, our nation's water problems have been front page news across the country. Everyone is aware of our tremendous surface water pollution problems, yet the threat to our vast underground water resources remains remote to most of the American public as well as to much of the scientific community.

With surface water resources decreasing in both quantity and quality, ground water, as the primary alternate supply, must be protected where it is pure, and improved where it is not. The technology to accomplish most of these tasks should be made available to the engineers, the architects, the planners, the managers, and, of course, the ultimate users.

In an effort to focus public and scientific attention on the broad and basic ground-water pollution problems, either present or developing, the first National Ground Water Quality Symposium was planned. Its objective was to

> "bring together the nucleus of men, methods and ideas capable of yielding solutions to problems which will insure the protection and restoration of the quality of our vast ground-water resources, whose development is destined to double and perhaps triple in the coming decade. It is intended that the published transactions of the Symposium will serve as a guide to the State-of-the-Art on ground-water quality."

In the following 211 pages, the reader should find that these objectives were met in a most comprehensive and useful manner. It is hoped that this manuscript will serve as a guide to potential problems and workable solutions which must be intelligently considered if our valuable resource is to be protected.

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EPA'S ROLE IN GROUND-WATER PROTECTION[a]

by Stanley M. Greenfield[b]

The Environmental Protection Agency's mission with respect to the nation's ground-water resources is not explicitly mentioned in the laws under which our predecessor agencies operated, nor is it mentioned in President Nixon's reorganization plan and message to Congress in July 1970 announcing the establishment of this new Agency.

It did not need to be mentioned specifically. It is implicit in all the water quality laws carried out by the Federal Water Pollution Control Administration and the Federal Water Quality Administration. It is implicit in the various public health laws under which the old Bureau of Water Hygiene established recommended standards for drinking water and gave technical assistance to municipal water-supply systems throughout the country.

Here is what the President said in his message to Congress in 1970 proposing the establishment of EPA: "Our national government today is not structured to make a coordinated attack on the pollutants which debase the air we breathe, the water we drink, and the land that grows our food. . . For pollution control purposes, the environment must be perceived as a single, interrelated system. . . The sources of air, water, and land pollution are interrelated and often interchangeable. . ."

"This reorganization," the President continued, "would permit response to the environmental problems in a manner beyond the previous capability of our pollution control programs. The EPA would have the capacity to do research on important pollutants irrespective of the media in which they appear, and on the impact of these pollutants on the total environment. . . This consolidation of authorities would help assure that we do not create new environmental problems in the process of controlling existing ones."

I think that is clear enough for anyone to understand. Water is water—a basic natural resource, whether it is on or under the surface of the earth. The nation's waterways, used for transport, industrial cooling and processing, recreation, and a host of other purposes, are surface waters; and a large part of our environmental protection efforts are to restore and maintain surface-water quality. But we are not limited to surface water. This would be absurd. A substantial portion of our total water is underground; in many parts of the nation the only water resource is underground.

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[a] Presented at the National Ground Water Quality Symposium in Denver, Colorado, August 25-27, 1971 (sponsored jointly by the Environmental Protection Agency and the National Water Well Association).

[b] Assistant Administrator for Research and Monitoring, Environmental Protection Agency, Washington, D. C. 20460.

And the line of demarcation between ground and surface water is indistinct. It's not a line but a continuum, variable from place to place and time to time. Ground water becomes surface water and vice versa. Both are parts of the same system, the hydrosphere.

There's an analogy here with the atmosphere. Ground water, especially the least-known portions that are deeply buried and move very slowly, can be likened to the stratosphere, which mixes very slowly with the troposphere below it, and in which pollutant gases or particles have very long residence times and slow fall-out. Yet in the recent public debate and discussion over possible pollution of the stratosphere by the supersonic transport plane, neither side argued that the thin upper regions of the atmosphere were too high up to be of environmental concern!

Ground-water quality is a legitimate concern of EPA, as this Conference demonstrates. It is probably true that lack of specific mention of ground-water resources *per se* in the laws and executive proclamations on which EPA is based has caused us to give ground-water problems less attention than other aspects of the environment during the first nine months of our official existence. This is an oversight—if you could call it that, perhaps "lack of emphasis" would be a better term—which we intend to remedy.

I endorse heartily the statement issued in October 1970 by the then Commissioner of the FWQA, on the disposal of wastes by subsurface injection—deep-well disposal. That policy order was clear and brief: two typed pages. After noting the increasing use of deep-well disposal of hazardous wastes, the risk of contamination pathways, the order put the FWQA on record as opposing such waste disposal "without strict controls and a clear demonstration" that such disposals will not harm "present or potential subsurface water supplies . . . or otherwise damage the environment."

The order then went on to list seven criteria to be "critically evaluated" for all proposals for deep-well injection:

1. Alternative disposal methods have been explored and *found less satisfactory* in environmental risk.
2. Appropriate preinjection tests have been made to allow prediction of what will happen to the wastes.
3. There is "adequate evidence" to show that the injected wastes will not interfere with present or potential resources and will not produce "other environmental hazards."
4. The best practical measures of waste pretreatment have been applied.
5. The injection system has been designed and built in the best possible manner.
6. Provision has been made for "adequate and continuous monitoring" of both the injection operation and its environmental effects.
7. The well will be plugged "below present or potential" water resources whenever its use is discontinued.

These seven caveats appear to give perfect protection. But they contain some circularities, some "weasel" words.

What constitutes "adequate evidence" that there will be no pollution?

Preinjection tests must "allow" prediction of what will happen to the wastes, but how reliable must these predictions be? And how long a time must they cover?

Pretreatment is obviously not as good as complete treatment, so why call it "best"?

How can alternative measures of disposal ever be considered "less satisfactory" in terms of environmental protection, when complete detoxification and neutralization of the pollutant is included as an alternative? How can we neglect to consider such complete treatment as an alternative?

What constitutes "adequate and continuous monitoring"? And when a disposal is sealed off, does the monitoring continue? How long?

The FWQA policy statement concludes with a ringing declaration that we recognize all subsurface injection as a temporary means of disposal, to be abandoned when better methods are developed, giving greater environmental protection.

There appears to be a kind of schizophrenia here.

Waste materials that we dare not release to that part of the environment we know the most about—the air, surface waters, and the top layers of the land—can be safely contained by pushing them farther down, where our knowledge of fluid movements and physical and chemical and biological changes is very scant indeed. It is just such out-of-sight, out-of-mind attitudes and actions that have brought about our present pollution problems.

To say "this is only a temporary expedient till we find a better disposal method" just glosses over the unpleasant truth that we are doing things we have condemned in others.

There is a parallel in the current concern over dumping wastes at sea. It has long been assumed that if you take the stuff out far enough and sink it deep enough, no harm will result—that the oceans are so voluminous they can dilute anything to innocuous levels. The Irish poet, Oliver Gogarty, 75 years ago expressed it thus: "And up the back garden, the sound comes to me of the lapsing, *unsoilable,* whispering sea."

We know that he was wrong; the sea is soilable. The earth's crust is soilable too, and vulnerable to damage by man's activities, not only in ways that we may predict and make allowance for, but also in unexpected ways.

For example, the problems of liquid waste injection are not simply of a geological and hydrodynamic nature. The problem of the thermal and chemical fate of the waste materials should have a major role in determining the areas and amounts of allowed disposal.

The result of not considering the chemical-heat problem was demonstrated when the Hammermill Paper Co., in Erie, Pennsylvania, began operating a sixteen hundred foot well in a dolomite formation. Approximately fifty-five thousand barrels per day of spent sulfite liquor containing a fiber, titanium dioxide, clay and lignin-like compounds were pumped into the well at pressures of eleven to thirteen hundred pounds per square inch between 1964 and 1968. When the well blew up, one hundred fifty thousand gallons per day of waste were spewed into Lake Erie. Apparently the well blew when the injection tubing corroded and the underground pressure was released to the casing.

The most dramatic instance of unexpected problems, of course, was the apparent stimulation of earthquakes in 1962 and 1963 and again in 1964-66 by the injection of liquid wastes two miles below the Rocky Mountain Arsenal near Denver, Colorado. Less dramatic—but probably more important in the long run—are the instances of gradual but massive changes in ground-water levels and ground-water quality by mining, by oil and gas drilling, by saline water injection, and also by pumping up ground water faster than its natural recharge rate.

Just as the cure of schizophrenia begins with recognizing that we have the disease, so there is great therapeutic value in candidly acknowledging that protecting the nation's ground water, and deep-well waste injection are likely to collide.

They are not mutually exclusive, however, any more than septic tank sewage systems are mutually exclusive with surface-water quality. Both can co-exist with the proper controls. If the soil is of the right type and is not overloaded, the physical, chemical, and bacterial processes will completely purify the sewage and maintain the quality of the surface water.

Our specific problems with deep-well injection are: first, how to identify and classify areas of safe injection so that fresh water aquifers are not encroached; second, how to determine what volumes of wastes can be injected safely; third, how to establish chemical standards on wastes to minimize the dangers of injection; and fourth, how to monitor and record deep-well injections to insure the engineering standards of their operation.

We have built up a considerable body of knowledge about ground-water supplies, recharge times, flow rates, and the fluctuations that can be expected over long periods of time. We need to know a lot more, of course, but we should not denigrate the knowledge we have, which has been vital to our existence.

We have long experience with deep-well injection—tens of thousands of injection wells in oil and gas fields, for instance—both for the disposal of unwanted brine and for the stimulation of flow from wells that have been depleted.

This long experience, however, has not been properly monitored in the sense expressed in the FWQA criteria previously mentioned. Oil men, in general, have been concerned only with getting rid of the stuff. When they put it back in the same zone from which they extracted the oil and gas, there is little change in the fluid gradient; the natural dynamic conditions are at least partially restored. But I am informed that the current and increasing practice is to return the brine to some other zone—

usually the shallowest available salt-water aquifer—from which the chance of migration into fresh-water aquifers or surface waters is great. This has already happened in certain parts of Texas and Oklahoma. It doesn't happen immediately but over a considerable period, maybe years after the injections start, so it is hard to trace and to establish the cause.

Arthur Piper of the U. S. Geological Survey has suggested the possibility that the noxious chemical wastes whose injection triggered the earthquakes at Denver might eventually migrate eastward to outcrops and ground-water source areas in Nebraska, hundreds of miles away. Piper said that might take several thousand years. He expressed the hope that "over that space and during that time the waste will have been rendered harmless by sorption, dispersion, and degradation. . . Data for assessing the hazard definitely are neither at hand nor readily obtainable. . . For the most persistently noxious wastes, a responsible society cannot knowingly create even a remote hazard."

It seems to me that the Denver earthquakes—and similar, less intensively studied cases in oil fields in western Colorado, Texas, and Utah—have served a very good purpose in alerting us to this kind of long-term danger. There's nothing like an earthquake to arouse public interest! And we need public interest if we are to get support for the research needed to find out what happens down there in the dark and the heat and the pressure.

We in EPA have a clear call to study, test, and evaluate all aspects of the ground-water environment. This includes, but is not limited to, the use of that environment as a depository for wastes.

Our research and monitoring efforts will be designed to complement and not conflict with those of the Geological Survey, NOAA, and other governmental agencies, both State and Federal, that are concerned with land and water use.

Above all we will need basic research in what happens to water and other fluids down there in the dark and the heat and the pressure.

To accomplish this task, we must take full advantage of the myriad of talents and resources that are available at the universities, in the States, in other Federal agencies, and in the private sector. This Symposium has resulted from our association with Dr. Lehr and the National Water Well Association. It has proven to be one with many worthwhile aspects. It has collected those in the field of ground-water resources who in their infrequent idle hours, I am sure, have resolved many problems and found new approaches to those yet unresolved. I think this gathering will go a long way to show collectively the importance of sound water resources development and more importantly the need for protecting our vast underground supplies of fresh water. Perhaps by our association with those of you working with the day-to-day aspects of ground-water management, and our association with the diverse membership of the National Water Well Association, we can achieve that most important goal in research—the goal of transferring technology from the laboratory to those who must ultimately make it work. If it has made a start in that direction, then this Symposium has most assuredly been successful.

A while back I quoted an Irish poet on the sea. Now I'd like to quote another Celtic bard, the Welshman, Dylan Thomas: "The force that drives the water through the rock, drives my green age."

We need to know a lot more than we do about the force that drives the water through the rock. If we are to have a "green age" for ourselves and our posterity, we need pure and abundant water in the ground.

The Contributions of C. E. Jacob to Scientific Hydrology and Engineering Works[a]

by Zane Spiegel[b]

ABSTRACT

C. E. Jacob was the first of a small group of hydrologists who followed C. V. Theis' lead in application of the theory of nonsteady boundary value problems to both well hydraulics and regional ground-water movement. Some of his scientific contributions were the explanation of the storage and elastic properties of artesian aquifers, the semilog method of aquifer test analysis, methods of analysis of tests on unconfined leaky aquifers, application of doublet theory to paired polarized heat-pump wells, the theory of step and constant-head aquifer tests by wells, salt-water encroachment, the tutelage of hydrology students at several universities, solutions to hundreds of field problems encountered in his extensive consulting activities in many parts of the world, and his method of determining aquifer recharge and transmissivity from the response of water levels in wells to varying natural recharge. One of his last works was a study of the natural recharge to Southampton on Long Island, which showed that the recharge was much less than the 21 inches per year assumed previously.

I would like to acknowledge the cooperation of several of C. E. Jacob's clients and close associates in the preparation of this paper, among them C. V. Theis, Stan Lohman, John Ferris of the U.S. G.S., and Bill Guyton, formerly of the U.S.G.S., and especially to Bettie Morgando of the firm of C. E. Jacob and Assoc., who is still working very hard for the firm to take care of all the details involved in settling his business affairs.

The purpose of this Symposium, as stated on the cover of our Program Guide, is "to bring together a nucleus of men, methods and ideas capable of yielding solutions to problems which must be solved to insure the protection and restoration of the quality of our vast ground-water resources, . . . " C. E. Jacob has already provided the means to solve many of our problems, if we could look at his many reports, particularly in his last twenty years of consulting.

C. E. Jacob began his career in ground water with field experience with the U. S. Geological Survey. Assisting R. M. Leggette, he made detailed studies of water level changes in the complicated aquifer systems of Croton Valley and Long Island, New York. This work gave him the practical experience needed to arouse his scientific interest in *learning* and then *explaining* the physical and mathematical basis of observed phenomena. He was the first of a small number of hydrologists who followed the lead of C. V. Theis in applying the theory of nonsteady boundary value problems to both well hydraulics and regional ground-water movement, in the English language.

In his first five years of experience, several important papers were published on the storage and elastic properties of aquifers in coastal plain sediments. These properties had been recognized qualitatively by Theis previously, but Jacob provided the first quantitative explanation of artesian storage, related this explanation to the tidal and barometric effects noted by others, first recognized the effects of railway trains on water levels, and later coined the term "storativity" which unified storage concepts. As a result of his detailed acquaintance with highly permeable areas of Long Island and Texas, Jacob was the first American hydrologist to connect the fact that natural fluctuations in water levels of wells are the best indicators of rates of recharge to aquifers with the theory of nonsteady boundary-value problems, to give a direct method for determining both the true recharge rate and the average effective transmissivity. This method requires the selection of only one assumed or independently determined value–the specific yield. Perhaps due to man's natural inclination to be more concerned with disturbances caused by himself than with those caused by natural phenomena, Jacob is best remembered for his contributions to understanding of storativity, the interpretation of the extremely valuable semilogarithmic plots of pumping tests, and the generalization of Theis' model for aquifer test analysis to tests on unconfined and leaky artesian aquifers, and to step tests and determination of effective well radius. Interchange of ideas with more experienced Survey hydrologists such as Theis, Lohman, Ferris, and Guyton contributed greatly to the success of his early research. An example of the value of this kind of interaction was the 1952 publication by Jacob and Lohman of a solution to the constant-head well problem which is useful in areas of flowing wells. His ability in mathematics permitted coordination with the ideas of Muskat and Hubbert developed in the petroleum industry.

Twenty-five years before a logical terminology and system of consistent units were agreed to by the profession, Jacob was appointed by Stan

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

[b] Ground-Water Hydrologist, P. O. Box 1541, Santa Fe, New Mexico 87501.

Lohman to chair a subcommittee of the American Geophysical Union to improve usage of the term permeability and its units. Many of the subcommittee's recommendations in 1946 were finally adopted by another committee chaired by Lohman after many thousands of students and self-taught hydrologists had labored with the ridiculous system Jacob and others had tried so long to improve.

The end of his first fifteen years of remarkable original contributions to hydrology was marked in 1950 by publication of the well-known chapter on "Flow of Ground Water" in the treatise "Engineering Hydraulics." This work summarized the results of most of his original work to that date. A large proportion of this important work was his original work.

Some of the important topics of that work were (1) a brief exposition of Darcy's Law correctly stated in terms of hydraulic head, *not pressure*, in a form similar to that of Hubbert's correction of one of the many unfortunate fallacies in hydrology; (2) a discussion of the range of validity of Darcy's law; (3) the difference between the terms permeability and transmission constant; (4) the velocity potential; (5) derivation of differential equations and their relation to boundary-condition equations; (6) the range of validity of steady radial-flow equations; (7) the effect of a well on a uniform flowfield, (8) recirculating pairs of wells (doublets) and well-stream systems; (9) the general theory of images; (10) specific capacity; (11) the superposition theorem; (12) tidal fluctuations; (13) well characteristics; (14) effects of a well between two parallel streams; and (15) adjustments for unconfined flow.

The next few years (the early fifties) are notable for the large number of important studies that were made, not so much by himself, but by his colleagues and students, on various types of well models and on more detailed aspects of the correlation of precipitation and ground-water levels on Long Island. These years were especially important for the beginning of publication of an astounding number of papers on well hydraulics and stream-connected flow by Prof. Mahdi Hantush, Jacob's most renowned former student.

After 1947, as ground-water consulting became Jacob's dominant activity, formal publication of important discoveries waned, but his characteristic custom of attacking a practical problem with new methods continued. Engineers, like Cipolletti, have been honored by having structures they designed named after them, but the great engineering works that benefited from Jacob's analyses in his last twenty years have neither his name nor a surface expression, and for many of the works, even his reports are only obscure sections of large tomes by the engineering firms to which he rendered able assistance.

Much of Jacob's work was done as a "consultant's consultant," wherein he provided a broad knowledge of ground-water principles and a phenomenal ability to solve problems. Most of his work can be classified in categories such as (a) the effects of a given water-supply development; (b) the mechanism and effects of mine drainage; (c) the effectiveness of drainage by wells; (d) well injection procedures; and (e) the control of uplift pressures near dams.

The scientific contributions contained in many of these reports may some day be considered as important as those of his first fifteen years of hydrologic contributions. Jacob developed a form for his major consulting reports that might well be taken as a model by consultants in many fields. Typically, these reports contained a synopsis giving his important conclusions; a concise statement of the problems and the circumstances which led to his involvement in them; a section on the important physical principles on which his analyses were based, with detailed references, many of which were his own; definitions of special technical terms used in the report; a concise summary of the geographic, geologic and hydrologic aspects of the problem; and finally the hydrologic core of the report, which frequently contained significant original contributions to scientific hydrology or engineering practice. In addition, it was his practice to add detailed appendices of the basic data on which he based his conclusions.

The detail and originality of Jacob's treatment of all the sections of his consulting reports can be fully appreciated only by reading these reports. I hope that some day a complete catalog of his works can be made available to the hydrologic profession, and that the full reports will eventually be made available for reference. Many of the consulting reports have already been released for public use, and efforts are being made to obtain the release of the others. New Mexico Institute of Mining and Technology in Socorro, New Mexico, has been designated custodian of these important contributions. The task of cataloguing Jacob's works for general library use is an enormous effort, far beyond the present resources of New Mexico Tech. If, during these three days, an effort to obtain additional support for this task can be initiated, the dedication of this Symposium to the memory of C. E. Jacob will take on a new meaning.

One of the most interesting characteristics of Jacob's wide range of consulting reports was the emphasis which he put on a careful description of the long-range effects of each project with which he was associated. This emphasis was undoubtedly due to his recognition that neither the public nor his clients were generally aware of the inevitability of diversion of streamflow by wells, the far-reaching effects of wells in slightly leaky aquifer systems, and the effects of aquifer nonhomogeneity on the rate of movement of contaminants. His understanding of hydraulic effects in complexly layered aquifers led him to conclude in several reports on both agricultural and mining problems that drainage works were more effective if installed in deeper semiconfined beds than in the shallow aquifers that ultimately were to be dewatered. This concept was applied in the Yuma area to reduce the number of wells needed to accomplish a given depth of drainage.

The great magnitude of effects of many of the projects which Jacob studied inevitably has brought about considerable controversy, or at least concern, as to the public welfare. For example, the economy of the entire country of Israel is dependent on the validity of computations made on the basis of Jacob's theories; enormous costs are at stake in the drainage of the Indus Valley in West Pakistan; international relations may be affected by the success or failure of the Yuma drainage project in southern Arizona, along the Mexican border.

Through many years of activity in problems of production of fresh water in areas underlain by salt water, Jacob recognized that future generations would be faced with enormously serious shortages of fresh water. As a result of this foresight, in 1965 he patented two improved methods for producing fresh water from wells. Negotiations are in progress by Jacob's estate to develop and test these patented methods.

In recent years possibly one of the most significant contributions to society made by the hydrology profession was a report on "Evaluation of Potential Impact of Phosphate Mining on Ground-Water Resources of Eastern North Carolina," prepared by a Board of Consultants of which Professor Jacob was Chairman. The report, made for the North Carolina Department of Water Resources in 1967, is typical of Jacob's reports in form and content. While the report contains a standard application of the well-accepted techniques of basin-wide engineering analysis, based on his own leaky-aquifer theory, it also contains one special feature that distinguishes it from most other reports of this type—a review of certain aspects of water law, with a recommendation for the enactment of State legislation establishing a permit system for all new large uses of ground water.

As a direct result of this report by Jacob's Board of Consultants, the North Carolina General Assembly enacted the "Water Use Act of 1967," which requires a permit from the State for large diversions of surface or ground water in any area previously declared to be a "capacity-use area." The legislation follows Jacob's recommendations closely. The rapid action of the North Carolina General Assembly in adopting Jacob's recommendations is evidence of the clarity and forcefulness of the report.

One of Jacob's last consulting reports (December, 1968) was an extension of earlier work by himself and Boris Bermes, a former student at the University of Utah, in which he applied variations of his important nonsteady mathematical model of water-level fluctuations to Southampton, a peninsular portion of Long Island. Using a value of specific yield that had been determined by detailed U.S.G.S. studies in a nearby area, he computed values of average annual recharge ranging from 8 to 14 inches per year, substantially lower than the previously accepted value of 21 inches per year that had been based on very rough estimates. Although engineering consultants working on similar problems in central and eastern Long Island had rejected Jacob's method and conclusions, the basic data available for similar areas of Long Island, southern New Jersey, and Cape Cod confirm Jacob's conclusions. Detailed analysis of all the factors affecting recharge have revealed valid reasons for the lower values he computed. Re-evaluation of Jacob's 1945 recharge computation for central Long Island on the basis of a revised specific yield of 0.25 gives a recharge value of 16 inches per year, correlative with those determined from Jacob's later Southampton work. Revised ground-water outflow computations, based on transmissivity values determined by correct applications of Jacob's semilog and leaky aquifer methods of analysis, and by refinements of Jacob's methods by Hantush, corroborate the conclusion that Long Island's recharge (and hence natural discharge) is much closer to Jacob's value of 16 inches per unit area than to 21 inches per unit area per year, based on the convenient roundness of the ratio 21 to 42 inches of precipitation. The implications of a twenty percent overestimate of the natural water supply are enormous, when it is recalled that water-supply projects do not generally contain any factor of safety, and millions of people may depend on the consequences of a rough estimate.

In the final analysis, it may come to pass that Jacob's real contribution will be recognized to be the foundation which he laid for a greater *social awareness* of the importance of water in our future life, by the combined effects of all his scientific and engineering studies. No matter what you or I do to attempt to solve these problems, no real solution will be attained without this social awareness by ourselves and the public.

Subsurface Disposal of Liquid Industrial Wastes in Alabama—A Current Status Report[a]

by William E. Tucker[b]

ABSTRACT

Four subsurface disposal wells have been drilled and completed in Alabama. These are: Stauffer Chemical Company, Mobile County; Ciba-Geigy, Inc., Washington County; U. S. Steel Corp., Jefferson County; and Reichhold Chemicals, Inc., Tuscaloosa County. The Geological Survey of Alabama has been directly involved in all four projects. The Survey served as a consultant to the Alabama Water Improvement Commission, the State agency responsible for protection of surface and ground water in Alabama, on the Stauffer and Ciba-Geigy projects, and as consultant and supervisor on the U. S. Steel Corporation and Reichhold Chemicals, Inc., projects. These projects were undertaken as a research effort to insure that the responsible State agencies are fully cognizant of all aspects of this method of waste disposal. It is a policy in Alabama that subsurface disposal is permissible for some wastes if the well is properly designed and completed in an appropriate geologic environment and if conventional methods of waste treatment have been evaluated and proved to be inadequate.

The Stauffer well, operating at 75 gallons per minute and 500 psi, is the only subsurface disposal system, other than oilfield brine disposal wells, that is currently in operation. The Stauffer and Ciba-Geigy wells are in the Coastal Plains geological province and the U. S. Steel and Reichhold Chemicals, Inc., wells are in Paleozoic sediments of the Warrior Basin. A general discussion of the geology, drilling, completion, and testing techniques is presented for the two geologic provinces involved.

INTRODUCTION

The transition of Alabama in the last ten years from a raw material producing State to a manufacturing State has placed an increasing burden on our water resources. In 1965, the State legislature amended the Water Improvement Commission Act creating an agency to protect the surface- and ground-water supplies of our State and removing the grandfather industries from exemption. The Geological Survey of Alabama is authorized by the legislature to conduct studies on the occurrence and availability of surface and ground water. This responsibility has been expanded to consider water usage and the environmental impact of industrial and population evolution. The Survey serves as a consultant to the Water Improvement Commission in the fields of geology, hydrology, and geologic engineering.

As subsurface disposal of industrial waste became popular in the middle 1960's, the Survey undertook research projects to determine any and all aspects of this method of waste disposal. To date the Survey has served as regulatory supervisor on three wells and directed the total program on two wells. In January, 1971, a general policy was adopted by the Alabama Water Improvement Commission regarding subsurface disposal in Alabama. The general policy approved of this method of disposal provided that all other methods had been examined and exhausted; and geologic and hydrologic conditions exist such that the environment is protected to the maximum extent possible.

Application for a subsurface disposal system in the form of a feasibility study is made to the Alabama Water Improvement Commission. The Geological Survey reviews the material presented and makes its own recommendation to the Commission. If the plan is approved, the applicant is allowed to drill and test the well. The applicant then applies for permission to utilize the well and information gathered while drilling and testing is reviewed by the Survey and further recommendations regarding use, requirements, and monitoring procedures are prescribed. So far, five subsurface disposal wells have been drilled and completed in accordance with this policy. These are: (1) Stauffer Chemical Company at Mobile; (2) Ciba-Geigy at McIntosh—2 wells; (3) U. S. Steel in Birmingham; and (4) Reichhold Chemical in Tuscaloosa (Figure 1).

GENERAL GEOLOGY

In order to form a geologic frame of reference, the State can be divided into three major geologic provinces. These are: (1) the Crystalline area in east-central Alabama, (2) the Warrior Basin in northwest Alabama, and (3) the Coastal Plains in

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

[b] Geological Survey of Alabama, P. O. Drawer O, University, Alabama 35486.

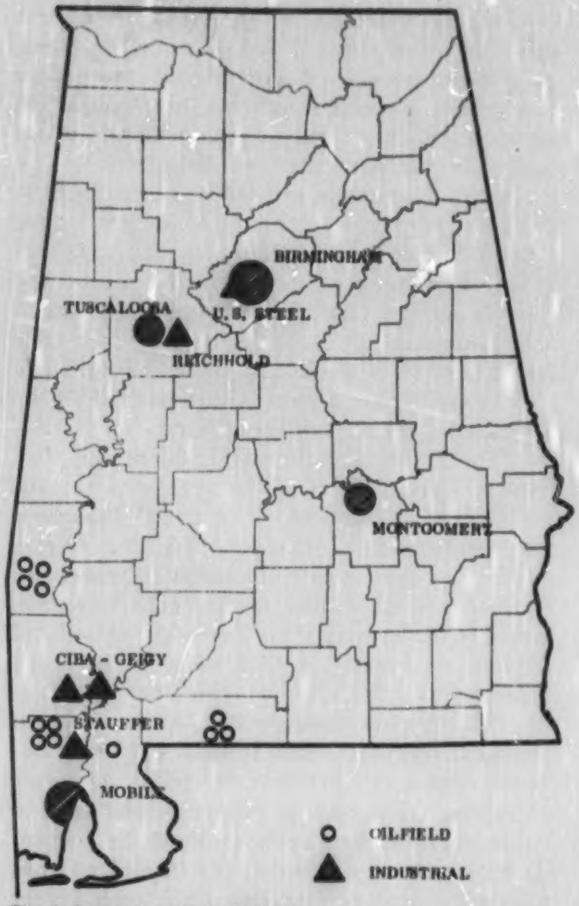
BIRMINGHAM
U.S. STEEL
TUSCALOOSA
REICHHOLD
MONTGOMERY
CIBA - GEIGY
STAUFFER
MOBILE
○ OILFIELD
▲ INDUSTRIAL

Fig. 1. Disposal wells in Alabama.

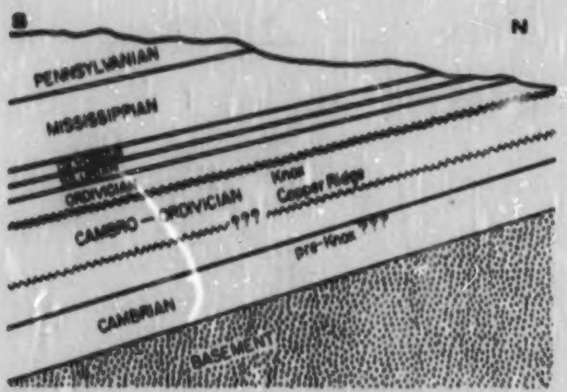
S
N
PENNSYLVANIAN
MISSISSIPPIAN
ORDOVICIAN
CAMBRO – ORDOVICIAN
Knox
Copper Ridge
???
pre-Knox ???
CAMBRIAN
BASEMENT

Fig. 2. Generalized cross section of north-central Alabama.

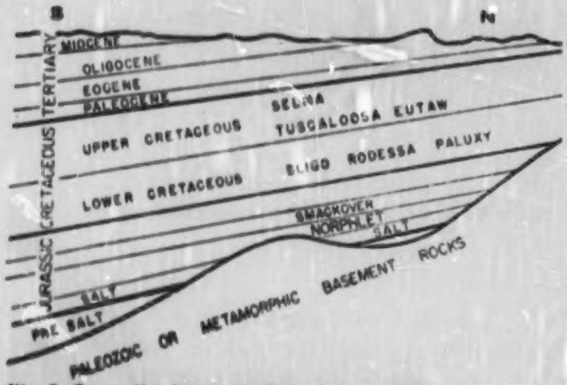
S
N
TERTIARY
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
SELMA
TUSCALOOSA EUTAW
CRETACEOUS
UPPER CRETACEOUS
SLIGO RODESSA PALUXY
LOWER CRETACEOUS
SMACKOVER
NORPHLET
SALT
JURASSIC
SALT
PRE SALT
PALEOZOIC OR METAMORPHIC BASEMENT ROCKS

Fig. 3. Generalized cross section of south Alabama.

south and southwest Alabama. A cross section through the Warrior Basin exhibits sedimentary formations ranging from Pennsylvanian to Cambrian in age. Disposal horizons are chiefly available in the Ordovician and Cambrian Ordovician by virtue of secondary porosity in the form of fractures and solution cavities. A cross section through the Coastal Plain area exhibits sedimentary rock from Miocene to Jurassic age with disposal horizons available in all formations by virtue of intergranular porosity in sandstones and secondary porosity in limestones and dolomites.

The Stauffer and Ciba-Geigy wells are in the Central Gulf Coastal Plain geological province and the easternmost extension of the Mississippi Interior Salt Dome Basin. Most of the geologic structures found in Lower Cretaceous or younger sediments in this basin are the result of movement of the underlying Louann Salt. Salt at depth, responds as a plastic medium and will move into zones of weakness in response to sediment loading. Structures formed as positive features by salt swells or domes and as collapse-type features such as grabens where salt was removed occur in southwest Alabama (Figure 4).

The most prominent structural features within the salt basin in southwest Alabama are the Hatchetigbee anticline, the Jackson fault-Klepac dome, the Mobile graben, and the Gilbertown-Coffeeville-West Bend, Pollard and Bethel fault zones. Other important structures are the domal anticlines at Citronelle, South Carlton and Chatom and the piercement salt dome at McIntosh.

A complex, north-south oriented fault system known as the Mobile graben extends from Jackson, Alabama, south to Mobile Bay. The Jackson fault is the northernmost fault on the east flank of the graben system. It is downthrown to the west and in the subsurface exhibits approximately 5,000 feet of throw at a depth of 2,450 feet where it was penetrated by the Champion Klepac No. 1 well drilled by Humble Oil and Refining Company in 1955. The large amount of displacement probably resulted from subsidence as salt was being removed to supply domal growth of the Klepac dome on the upthrown site.

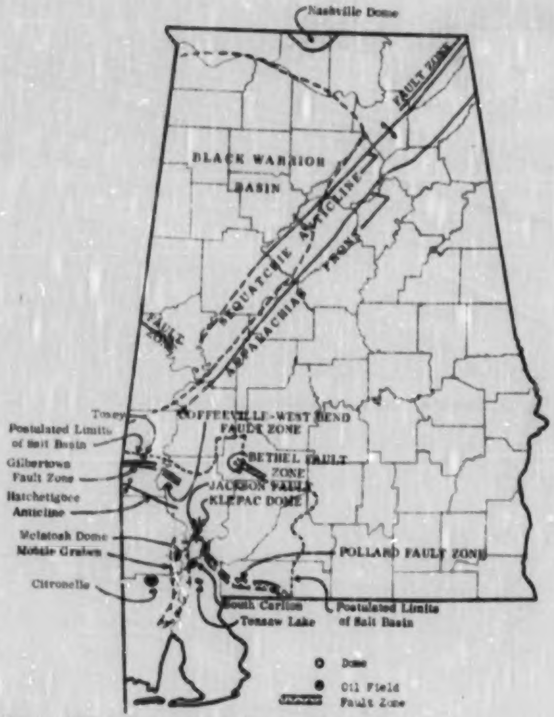

Fig. 4. Major structural features in Alabama.

The major fault representing the west flank of the graben opposite the Jackson fault has never been penetrated. It is possible that the northern part of the Mobile graben is only a half-graben where the Jackson fault comprises the east flank of a structural low.

Farther to the south, faults representing both east and west flanks of the graben have been mapped. The graben, as determined from existing well control, turns westward north of Mobile Bay and can be projected into Mobile County west of the Bay.

The McIntosh salt dome in Washington County is the shallowest piercement salt dome in the Mississippi Interior Salt Dome Basin. The dome pierces Miocene sediments within 410 feet of the surface of the ground and is approximately 1 mile in diameter. There is little or no well control for structurally mapping radial and peripheral faulting commonly associated with the piercement salt dome. The location and configuration of the rim syncline immediately adjacent to or surrounding the McIntosh dome is interpretive. It is believed to have been formed by subsidence above the area where salt flowed toward the center of the salt dome.

The deposits of Late Cretaceous age in Alabama crop out in a crescent-shaped belt across the central part of the State. In western Alabama these beds dip southwestward and, in ascending order, include the Tuscaloosa Group, which comprises the Coker and Gordo Formations; the McShan and Eutaw Formations; and the Selma Group, which comprises the Mooreville and Demopolis Chalks, the Ripley Formation, and the Prairie Bluff Chalk. In eastern Alabama the beds dip southward and the chalk formations of the Selma Group merge laterally into formations consisting chiefly of sand and clay. Along the Chattahoochee River deposits of Late Cretaceous age, in ascending order, are represented by the Tuscaloosa Group (undifferentiated), the Eutaw Formation, the Blufftown and Ripley Formations, and the Providence Sand.

The Upper Cretaceous Series includes two important faunal zones, the *Exogyra ponderosa* and the *Exogyra costata*, that can be traced throughout the Atlantic and Gulf Coastal Plains. The *Exogyra ponderosa* zone extends stratigraphically from the Tombigbee Sand Member of the Eutaw Formation almost to the bottom of the Ripley Formation, and the *Exogyra costata* zone extends from the top of the Demopolis Chalk to the Prairie Bluff Chalk.

The Tertiary formations in Alabama consist predominantly of marine clastics, and are transitional in character between the clastic and largely nonmarine formations of Mississippi and the carbonate rocks of the Florida peninsula. In Alabama the Paleocene, upper Eocene, and Oligocene formations grade into limestone; one of the lower Eocene formations grades into limestone downdip in the subsurface; and the middle Eocene formations become increasingly calcareous eastward. Alabama and northwestern Florida are included in the eastern part of the North Gulf Coast sedimentary province characterized by clastic deposits chiefly, in contrast to the carbonate anhydrite facies in the Florida peninsula sedimentary province (Toulmin, 1955).

The U. S. Steel and Reichhold Chemicals, Inc., wells are in Paleozoic formations. Geologically, the Reichhold plant site is located in the Black Warrior sedimentary basin. The Black Warrior is a wedge-shaped basin extending across Alabama and Mississippi and contains considerable thickness of clastic and carbonate sediments. The basin is a negative feature bounded to the north by the Nashville dome, to the east and south by the ridges and thrust faults of the Appalachian front, and extends to the west into the State of Mississippi.

The geologic structure in most of the Black Warrior basin is fairly simple, with formations generally dipping to the south or southwest. In Alabama, the salient structure existing in the Black Warrior basin is the Sequatchie anticline. This anticline, a subsurface extension of one of the Appalachian foreland ridges, plunges beneath the surface in Blount County, Alabama, and probably extends far to the southwest, perhaps as far as the Mississippi State line. The Sequatchie anticline in the subsurface has been referred to as the Blountsville or Browns Valley anticline. The Sequatchie anticline passes beneath Tuscaloosa County, but the axial trend fades out and cannot be traced on the surface beyond the eastern half of the county. Semmes (1929) shows the anticlinal axis turning south in Tuscaloosa County, but detailed structural mapping supporting this trend is not included in his report. The existence of an unconformable Cretaceous veneer over the western part of the county prohibits the use of Pennsylvanian outcrops in tracing the trend of the anticlinal axis. Moreover, thickening of Pennsylvanian sediments to the southwest along the direction of axial plunge of the anticline coupled with the unconformity existing at the Mississippian contact may tend to mask the trend of the Sequatchie anticline in the older and deeper sediments, from reflection in the Pennsylvanian.

Semmes (1929) shows the Warrior syncline, the complimenting structure to the north of the Sequatchie anticline, trending northeast to southwest with the axis passing a few miles east of the city of Tuscaloosa. For the reasons given previously, it is possible that the main structural axis of both the Sequatchie anticline and the companion Warrior syncline extend to the southwest as far as the Mississippi State line with the dominant structural expression existing in pre-Pennsylvanian sediments. If this is the case, the anticline may pass north of the city of Tuscaloosa, and not be reflected strongly in Pennsylvanian age rock.

Detailed mapping of the coal beds of the Pennsylvanian sequence indicates that minor folding and faulting is widespread in sediments of this age in the basin. Anticlinal trends are local and tend to disappear rapidly. Faults show small displacement and are of limited areal extent. It is possible that many faults are confined to the Pennsylvanian and fade out before reaching the Mississippian. In general, the magnitude of folding and faulting in the Pennsylvanian decreases to the northwest away from the major thrust faults marking the boundary between the Black Warrior basin and the Appalachian front.

The Birmingham anticline is the major structural feature in the Fairfield area. It is a breached, asymmetrical anticline, trending northeast, underlain by limestones, shales, sandstones, chert, dolomite and some iron ore seams. Rocks from Cretaceous to Cambrian outcrop in the Fairfield area, with Jurassic, Triassic, and Permian rocks not being represented. The Mesozoic and Paleozoic sediments generally dip to the southeast except where folded or faulted.

Faults associated with the Birmingham anticline include thrust faults, strike-slip faults, reverse and normal faults, and relaxation faults. The geology of the area is often complicated by the presence of so many folds and faults.

Near Vance, Alabama, the Birmingham anticline plunges to the southwest and is overlain by Mesozoic sediments of the Tuscaloosa Group.

NATURAL RESOURCES

The Coastal Plain of Alabama is the most important ground-water producing area in Alabama. The consistent occurrence of good water-bearing sand and gravel beds make the development of large-capacity wells quite common. Most outcropping sands in this area are considered good to excellent aquifers. Water well depths vary from a few feet to 1,700 feet and yields range up to over 1,000 gpm (gallons per minute). Well yields in the Paleozoic vary considerably and, although topography is important in locating a successful well, the contributing factor for a high yield well is the penetration of solution channels and cavities within limestone reservoirs. Yields range from a few gallons to several thousand gallons per minute (350 to 3,500 gpm).

The Citronelle Field, the South Carlton Field and the Tensaw Lake Field are located in the area of the Ciba-Geigy wells and the Stauffer well. Salt, limestone, and lignite are other mineral resources that are being developed or have potential as mineral deposits in the Coastal Plain.

Mineral resources in the area of the U. S. Steel and Reichhold, Inc., wells are primarily iron ore, coal, and limestone.

DISPOSAL WELLS IN ALABAMA

Stauffer Chemical Company Well

The Stauffer Chemical Company disposal well was the first industrial subsurface disposal system drilled and completed in Alabama. This well was drilled to a total depth of 4300 feet, and eventually completed through perforations at 3400 feet with a tested injection rate of 420 gpm at a surface pressure of 400 psi. This well has been in operation for 2½ years without interruption, except for a remedial acid treatment.

Ciba-Geigy Wells

The Ciba-Geigy Corporation has drilled two subsurface disposal wells. The first well was drilled to a total depth of 7500 feet and final completion has been effected at 3800 feet through a screen and gravel pack. An injection rate of 420 gpm at 800 psi has been established for this well. The number 2 well was drilled to 2500 feet and completed at 2000 feet through a screen and gravel pack. Fresh waters occur in this area to a depth of 600 feet. Surface casing has been set on each of these wells at approximately 1100 feet and cement circulated to the surface. The number 2 well has an injection capacity of 800 gpm at 300 psi.

Two wells have been drilled and completed in the older sedimentary rock of north-central Alabama. These were for U. S. Steel Corporation in Birmingham and Reichhold Chemical Company in Tuscaloosa. Both wells are of the open-hole completion type and penetrated the same rock units.

U. S. Steel Well

The U. S. Steel well has an injection capacity of 300 gpm at 600 psi surface pressure. The well was drilled and completed to a total depth of 6,072 feet. All operations were under the direct supervision of the Geological Survey of Alabama as a research project in the field of deep-well disposal of aqueous wastes. The project was financed by a research grant from U. S. Steel Corporation to the Alabama Geological Survey. All steps taken in the drilling and completion of the well were designed for the protection of surface and subsurface water resources and other natural resources of the area.

Electric logs, cores, drill stem tests, and injectivity tests run during the drilling of the well indicated the feasibility of completing the well as a deep-well disposal system. The disposal horizon was completed "open-hole" from 4,415 feet to 6,072 feet. The well was cased and cemented as follows:

16" casing set at 64 feet	–Cemented to surface
10¾" casing set at 1,100 feet	–Cemented to surface
7⅝" casing set at 4,415 feet	–Cemented to 2,720 feet
2⅞" injection tubing set at 4,434 feet	

The results of injection tests indicate that either of two zones have a sufficient capacity to handle the present volume of pickling liquor waste. The uppermost zone has the capacity of accepting a greater volume-rate at a lower pressure than the lower zone. The well is so constructed that the lower zone would commence to take fluid in the event the upper zone fails to function properly.

Injection tests run during and after the completion indicated the well's ability to receive fluid without pressure build-up. The absence of pressure build-up after extended injection indicates a salaquifer of considerable areal extent and capacity.

The primary injection zone, 4,415 feet to to 4,630 feet, is a fine grained, very calcareous sandstone with shale laminations. Porosity and permeability is present in the rock unit by virtue of fractures. The zone of secondary importance, 5,550 feet to 5,770 feet, is a dolomite with fractured porosity and permeability.

Due to the high percentage of carbonate material in the sandstone and almost total carbonate composition of the dolomite, consideration must be given the reaction between the waste $FeCl_2$ + HCL or $FeSO_4$ + H_2SO_4 and the formation constituents. Injection of waste HCl effluent into a carbonate formation will result in a dissolution of the soluble parts of the rock and will cause an increase in permeability, thereby increasing the injection rate and/or reducing the pressure required. The reaction products will be water, carbon dioxide, and calcium chloride--the latter two being soluble in water. Adversely, the pH increase resulting from these reactions may cause $Fe(OH)_3$ precipitate and possible plugging.

$$Fe^{+++} + 3(OH)^- = Fe(OH)_3 \text{ (gel precipitate)}$$

$$Fe^{++} + 2(OH)^- = Fe(OH)_2 \text{ (precipitate)}$$

In a sulfuric acid reaction with a carbonate formation, the calcium released will be reprecipitated as $CaSO_4$ (anhydrite) or $CaSO_4 \cdot 2H_2O$ (gypsum). The high iron content of the waste effluent (1.2 moles/liter) coupled with the pH increase from mineral reactions will cause precipitation of $Fe(OH)_3$ gel.

There is considerable controversy among experts as to whether the precipitation resulting from acid waste injection into a carbonate reservoir will plug the pore space and reduce permeability. Fortunately, experience has shown that low strength acid waste may be injected into carbonate strata. Hammermill Paper Company at Erie, Pennsylvania, and Dupont at New Johnsonville, Tennessee, have successfully injected acid waste into carbonate strata.

From all indications, the porosity of the injection zone in the subject well is fractured rather than intergranular. This should prove more favorable to acid injection because less surface area is available for reaction, and the "zone of reaction" should extend to a greater distance from the well bore. Considering the two extraneous precipitates caused by the reaction of H_2SO_4 with a carbonate compared with the HCl reaction, it must be stated that the HCl reaction would be more compatible with the salaquifer water and rock than the H_2SO_4

pickle liquor reaction. However, if the H_2SO_4 pickle liquor was reduced in acid strength by dilution of 1 part acid to 1 part water or 1 part acid to 2 parts water, there is no reason why the well and receptor formation should not function equally as well.

Reichhold Well

The Reichhold well has an injection capacity of 600 gpm at 700 psi. A generalized surface treatment facility includes pretreatment filtration, storage, further filtration and injection.

Initial feasibility and geological studies for the Reichhold well were made by the Geological Survey of Alabama and Deep Well Pollution Control Corporation. The results of this study were presented in a report entitled "Study of the Potential of Subsurface Disposal in the Tuscaloosa Area," dated September 30, 1968. All aspects of the project were under the direct supervision of the Geological Survey of Alabama as a research project in the field of deep-well disposal of aqueous wastes. The project was financed by a research grant from the Federal Water Quality Administration and Reichhold Chemicals, Incorporated. The objectives of this phase of the project were to design and complete a well that would assure protection of surface and subsurface water resources and natural resources of the area, and to locate a horizon in the deep subsurface formations that would be receptive to the plant's waste effluent.

As in the case of the U. S. Steel well, electric logs, cores, drill stem tests and injectivity tests run during the drilling of the well indicated the feasibility of completing the well as a deep-well subsurface disposal system. Permeability exists in two main horizons in the well. The upper zone is from 6620 to 6670 feet and the lower zone is from 7036 to 7230 feet. The upper zone is sandstone, pale red to light gray, very fine to fine grained, hematitic in part, calcareous, and quartzose. The lower zone is limestone, yellowish gray to very light brownish gray, dense to crystalline dolomitic and sucrosic in part. Permeability and porosity exist in both horizons by virtue of natural fractures and cavernous vugs.

Electric logs and drilling characteristics indicate a highly fractured zone in the Floyd Shale in the interval between 5070-5600 feet. A completion in this zone should be considered as an alternative should the lower two zones cease to function properly. This interval is presently cased off and cemented. A completion in this interval would necessitate a secondary cement job and perforations throughout the injection horizon.

SPECIAL TECHNIQUES

During the drilling of a disposal well, a geologist constantly examines cuttings and maintains a sample log. This information is used to determine zones of importance in which open-hole drill stem tests should be made. The drill stem tests provide formation pressures, producing rates and a sample of the reservoir fluid. Electric log techniques are used extensively to evaluate the formations penetrated and to determine potential injection horizons. The data collected while drilling the wells is utilized to determine the casing and cement program. Preliminary injection tests are conducted to establish rates and pressures that will be utilized in the design of surface equipment. A composite of this information is made for a graphical presentation and exhibits the results of drilling and testing a well. The most advanced logging techniques available were utilized in Alabama.

These included the dual induction lateral log, the borehole compensated sonic log, the formation density log, sidewall neutron porosity log, radioactive tracer log, and temperature log. Each of these logs is also recorded on magnetic tape and composited by computer in the form of a synergetic log which is a continuous record of all formations penetrated showing porosity, permeability, water saturation, and lithology. The cement bond log is useful in determining the amount of cement fill-up, and the degree of bonding between the casing and the cement, and the cement and the formation.

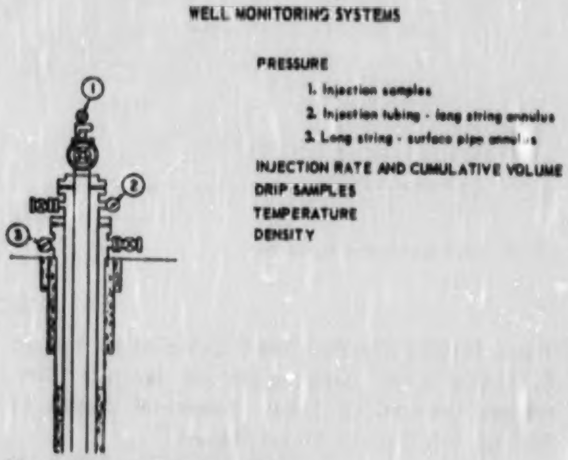
WELL MONITORING SYSTEMS
PRESSURE
1. Injection samples
2. Injection tubing - long string annulus
3. Long string - surface pipe annulus
INJECTION RATE AND CUMULATIVE VOLUME
DRIP SAMPLES
TEMPERATURE
DENSITY
①
②
③

Fig. 5. Well monitoring systems.

Temperature logs and radioactive tracer logs are run to determine the zone of entry of the injected fluid. When the well is placed in operation, the well must be monitored by continuous clock recorders, recording pressure at the injection tubing, the annulus between the injection tubing and long string and the annulus between the long string and surface casing (Figure 5). Injection rates and cumulative volumes are recorded on continuous clock recorders.

MONITORING TECHNIQUES

Drip samples of the wastes are taken and analyzed periodically. Temperature and density are recorded on a continuous basis and corrosion tags are analyzed periodically. Sample stations are set up on surface streams and water-supply wells are sampled periodically. Through an agreement with the Air National Guard, aerial photos (color and infrared) are made quarterly. An additional seismic monitoring system has been added to the Reichhold well to study any possible effects that injection may have on the tectonic activities of that area (Figure 6). The system consists of ten geophones placed around the well. The geophones are connected by a telephone service to a seismic recorder at the Survey office. Continuous films (16 mm) are made of seismic activities in the area. These are transmitted daily to the U. S. Geological Survey Earthquake Center at Menlo Park, California, for analysis. Two monitor wells will be drilled between the two injection wells at Ciba-Geigy and completed in the lowermost fresh-water aquifer. Samples from these wells will be analyzed periodically for changes in chemical quality.

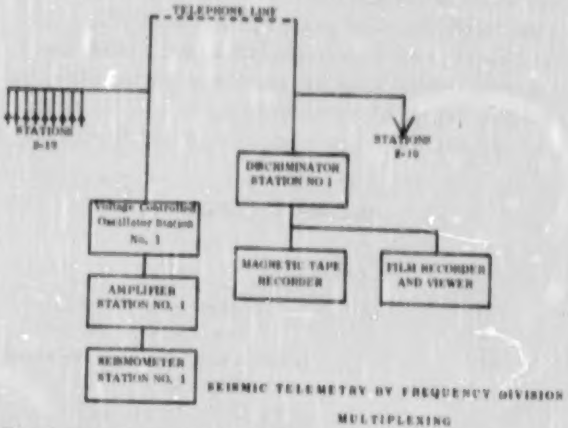
TELEPHONE LINE
STATIONS 2-10
STATIONS 2-10
DISCRIMINATOR STATION NO 1
Voltage Controlled Oscillator Station No. 1
MAGNETIC TAPE RECORDER
FILM RECORDER AND VIEWER
AMPLIFIER STATION NO. 1
SEISMOMETER STATION NO. 1
SEISMIC TELEMETRY BY FREQUENCY DIVISION MULTIPLEXING

Fig. 6. Seismic monitoring system.

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DISCUSSION

The following questions were answered by William E. Tucker after delivering his talk entitled "Subsurface Disposal of Liquid Industrial Wastes in Alabama—A Current Status Report."

Q. *We'd like to hear more discussion on whether conventional methods of waste treatment have been evaluated and proven inadequate. Example: Brines can almost always be disposed of in more conventional ways. Aren't we really speaking of economics?*

A. This particular brine is tremendously concentrated and, of course, I think economics definitely fit into any of these systems. The present conventional system, in this particular plant, has been to store the brine in a lagoon for evaporation. And, in an area where you have 53 inches of rain a year, it doesn't evaporate very much, and, of course, is inadequate. I'm not familiar with all of the chemical process techniques of separating brines—but most consume a tremendous quantity of energy creating other forms of pollution and, of course, introducing the economic question again.

Q. *Are you monitoring the effects of ingestion of acid wastes on the carbonate rock reservoir; and how do you determine the compatibility of the injection fluid with the reservoir fluid?*
A. Well, this causes no end of concern in the U. S. Steel well which will be a sulphuric acid injected into the carbonate reservoir. You can duplicate it in the laboratory with samples of the waste. When you lower the pH, you start getting precipitation of the sulphates. This is a problem that's in debate throughout the country. In subsurface disposal wells, will these precipitants harm the injection well? There are some active sulphuric acid injection wells that function perfectly well. But, when you see those precipitants come out of solution in the laboratory, it really scares you. We think that one advantage at the U. S. Steel well is the fractured system of porosity rather than intergranular porosity. Of course, the rock material will be in contact with the fluid, but it will eventually neutralize itself at a greater distance from the well. An option for that well, if precipitants clog the fractures, is to change the pickling process to a hydrochloric system and dispose of the WPL in the disposal well.

Q. *How does the Alabama Geological Survey determine and/or define the expression, "appropriate geologic environment," and also how do you determine an inadequate treatment method which would then indicate that you could—or should—consider deep well disposal?*
A. Well, the appropriate geologic environment is determined by the knowledge of the subsurface gained from data while drilling the well, reservoir parameters, porosity, permeability, compatibility, fractured gradients in the area, structural movements—all these factors that I've tried to present in the talk, are used to determine the appropriate geologic environment. At the same time, the well has to be mechanically constructed to conduct the waste to the disposal horizon and protect the fresh water resources. Each well is judged by its own merits in an evaluation-type decision. We do make laboratory compatibility studies of the waste effluent with the rock and with the formation water.

Q. *Does the Alabama Geological Survey expect to bear the cost of all monitoring of waste disposal wells drilled in the future? And will detailed monitoring be done on all waste disposal sites?*
A. Yes, we will bear the cost. This has been set up in our operational budget, allocated by the State Legislature. There are many areas, of course, where matching funds and research funds are available to help supplement these efforts. For instance, the seismic study and monitoring on the Reichhold is being financed by the USGS. The Environmental Protection Agency paid 23.3% of the total cost of the well and funds were budgeted for 5 years of monitoring the well. Detailed monitoring will be utilized on all waste disposal wells.

Q. *Comment on the need for rehabilitation of waste disposal wells—how often might you have to do this and what methods might you use?*
A. Typically, we think our monitoring procedures will turn up times that remedial work will be necessary. The Stauffer well was in operation for about two years before it required a remedial acid job to clean up the perforations. This is typical for a brine disposal well in an oil field or a producing well in an oil field.

Q. *Regarding the chemical reaction between acid waste and carbonate rock, how about the production of CO_2 and its effect on formation pressures?*
A. Since we are operating at 3,000 or 4,000 pounds pressure, most of the CO_2 will be in solution of formation fluids and spent acid water. Sometimes this reduces viscosity. CO_2 is not generally a problem unless the pressure is such that it comes out as solution.

Q. *Will there be publications describing these disposal holes, or disposal wells, or general information on the disposal program?*
A. Yes, we have in preparation a State-wide report on subsurface disposal which the Survey hopes to be able to release this fall.

Q. *How do injection rates compare between the Stauffer well, which was perforated—presumably with a jet perforation system—and the gravel packed Ciba-Geigy well? Do you see any problems involved with jet perforation for any injection well, especially in larger diameter wells in the 16 to 20 inch size?*
A. The Ciba-Geigy gravel-packed well presents higher injection rates at lower pressures. Of course, you get pressure drops, cross perforations because of friction loss. If the conditions are suitable, I think perhaps the enlarged hole, under-reamed prior to gravel packing, presents mechanically the best systems. In some cases, this is not practical, and incompetent formations will continually cave in and slough off into the well. The perforating technique doesn't lend itself very readily to, say, an acid injection. You would have acid in contact with the metal causing undue corrosion unless you used some type of exotic alloy steel.

Q. *Have you noted any decline in injection capacity on the one well that's been in operation for a couple of years?*
A. It did decline up to the remedial acid job, and the acid job restored the well to its former capacity.

Q. *For wells in which you are disposing of acid, and using a cement grout to seal the casing, this might readily dissolve—that is, some cement grout might readily dissolve if leaks develop. Why not use inert, or acid-resistant grout?*
A. Correct. In some cases, we use a resin-type of cement—that is, acid-resistant. Most often it is best to complete the well in such a manner that the waste will never be in contact with the cement. You may have noticed on the gravel-packs and open-hole completion that the waste is going down below the casing and cement and this prevents it from coming in contact with the cement. Some of the cement used is high density of about 15 or 16 pounds per gallon and it has a lot of nonreactive material in the cement. But, there are resin cements available, plastics that can be used if the situation develops.

Q. *The sense of this question asks whether hydrochloric acid is, in fact, a waste that could not be handled at the surface with conventional treatment techniques and, if that is true, then why is the decision made to use a disposal well for handling of hydrochloric acid?*
A. We would greatly encourage all industries to recover whatever products they can off of a waste stream. I think this is an area that will be the eventual solution to most of our waste problems. We have one steel industry in Alabama that has a hydrochloric acid pickling system and they reclaim all of the acid. This is, of course, the ideal solution—to restore and renew your waste. The U. S. Steel well will dispose of 125 gallons per minute of sulphuric acid, which is about 10 percent active. This is a tremendous amount of potentially useful material, and while these wells are in operation, we hope to continue to encourage companies to restore their waste. But, I think it is just something that will happen down the road quite some time off.

Q. *In the case of a State agency directed well disposal system for an industry, who bears the responsibility for possible contamination, the State or the industry?*
A. I imagine that would get into a pretty hairy legal situation. We were wearing the unusual hat of a consultant or prime contractor on these two jobs and I assume that the usual liability the contractor has for a completed project would exist.

Q. *What do you hope to see from air photo and infrared methods with regard to monitoring and injection systems and, an allied question, why do you want to fly side looking radar for monitoring?*
A. South Alabama, the Mobile area, of course has quite a few fault systems. We don't know for sure, but we think these faults are sealed as evidenced by the nature of the sediments, but we found these particular photographs very useful in our part of the country for picking out fracture traces, fault and joint systems and lineation on the surface. We have flown a side looking radar on hydrologic problems and were able to locate fault systems. If a subsurface disposal system has any possibility of leaking along fault planes we would like to know where. We feel that the infrared will show up the areas of tree kill or vegetation destruction. Because they are flown on a periodic basis we have a continuous historical record.

Q. *Two questions related to economics: first, what was the approximate cost to the industrial clients of deep disposal well planning and completion, and the other question—what are some typical costs of the disposal wells mentioned?*
A. In the case of the U. S. Steel well, the Survey received $30,000 for its participation. The cost of the well, including that $30,000 was approximately $240,000. On the Reichhold well, the total cost of the well was approximately $300,000 and the Survey received $50,000 for their participation. These figure out to approximately $30 a foot. This would compare closely with oil and gas drilling and completion in the same area. Oil and gas wells in this area usually run $10 to $15 a foot for a completed well, but they don't take quite the pains in testing and coring and sampling and logging. We used practically every tool available to the oil industry in our work. So, that's one factor that increases the cost.

Q. *Another one related to a former subject: have you had any complaints from consulting engineering firms about the Geological Survey of Alabama acting as a consultant in this way? Would some type of consulting by the State Survey be permissible outside Alabama and, lastly, did Alabama's Attorney General render an opinion on this?*
A. So far, we haven't had any complaints. I noticed Jack Talbot was in the auditorium and he is in this type of business, but he hasn't complained. Actually we have worked closely with consultants to the mutual benefit of both parties. I don't think we'd be interested in doing outside work, except contributing our experience to the state of the art. In fact, I doubt if it would be permissible for us to do otherwise. We did receive an Attorney General's opinion on this subject. Our legislative act enables the Survey to study all phenomenon associated with geology so we are given a pretty broad area of operation. The philosophy behind our being involved in this is that the

wells we were involved in were considerably removed from an area of active oil and gas exploration. It was in an area where the nearest exploratory well was 75 miles away, and we felt that we were more suited, knowing outcrops and knowing the stratigraphy, than perhaps a consulting firm from out of State. There are two more areas within the State where we would like to drill subsurface disposal wells. Again they are areas that we don't have much subsurface information about. Very likely we will be involved in those two projects, but I think it will end after that.

Q. *Do you have a monitoring system that will identify leaks early in the stage by monitoring over the injection zone, rather than waiting until a leak might be serious enough to come up to hit an aquifer which you are monitoring?*

A. None of the wells are presently set up to do that. We feel that we can use the pressures and injection rates, pressure fall-off curves and things like that to determine if there is a leak anywhere and these are recorded on time charts which are analyzed continually and irregularities will show up in the pressure recordings.

Q. *This, incidentally, was done by a geologist working in Colorado and he raises a good point. They have had to fuss with this for awhile. Has there been any noticeable seismic activity related to any of your disposal wells?*

A. No, there has not. I think I might have misied you on the seismic monitoring of the Reichhold well. That well is not in operation at this time. We are recording historical data prior to the actual injection of waste into that well. This should occur about the first of 1972. As far as seismic monitoring is concerned, the Reichhold well will be our main area of study—the seismic activity caused by the injection into the Reichhold well. We do not have seismic monitoring capabilities around the other wells in the State.

Subsurface Storage and Disposal in Illinois[a]

by H. F. Smith[b]

ABSTRACT

The storage of both liquids and gases in underground strata has become rather common in Illinois.

The problem of disposal of fluid industrial wastes has caused greatest concern, especially for the possible effects on ground-water quality. Necessary precautions have been established in the requirements of the Illinois Environmental Protection Agency (IEPA) which has authority to control, prevent, and abate pollution of streams, lakes, ponds, and other surface and underground waters in the State. Before any construction can begin on storage in subsurface strata, a permit must be secured from the IEPA. Eight basic design policies have been adopted that have to be met before a construction permit will be issued.

Sandstone, limestone, and dolomite are the basic lithologies most commonly considered as potential disposal reservoirs in Illinois. From well cores of such formations, essential laboratory studies are conducted defining the rate of fluid movement, porosity, and permeability of the rock and the pressure distribution within the aquifer.

Plugging of the injection horizon is the most serious cause of damage to a fluid injection system and results from the forming of an impermeable deposit on the well bore or plugging in the formation itself. In either case the plugging may result from a number of listed causes.

To date there have been four industrial waste disposal wells in Illinois. Variation in conditions is illustrated by these cases of disposal wells that have been authorized by the State.

The first practical use of underground gas storage in Illinois was at Waterloo in 1950. Since then, the number of projects and their capacities have grown continuously. At the present time there are 24 underground gas storage projects. Gas injection pressures must be kept below the fracturing pressure of the caprock. In underground gas storage reservoirs in Illinois, injection pressures of approximately 0.55 psi per foot are often used.

Secondary recovery by water flooding accounted for 73.4 percent of the total oil production in Illinois during 1968. In that year there were 880 active projects in Illinois with 13,107 water injection wells that injected 2581 million gallons of water.

INTRODUCTION

The storage of both liquids and gases in subsurface strata has become rather common in Illinois. These practices include: (1) storm water runoff with storage for only a few days, (2) artificial recharge for several months, (3) natural gas for a season, (4) brines for an indefinite period, and (5) industrial wastes for permanent disposal.

The problem of disposal of fluid industrial wastes has caused greatest concern, especially for the possible effects on ground-water quality. Necessary precautions have been established in the requirements of the Illinois Environmental Protection Agency, which has authority to control, prevent, and abate pollution of streams, lakes, ponds, and other surface and underground waters in the State.

As the State Legislature and the Federal Government, encouraged by conservation agencies, tighten controls on surface disposal and enforce existing legislation, the problem of fluid waste disposal will become considerably greater in the future.

The first major industry that was faced with high volumes of fluid waste disposal was the petroleum industry, which produced large quantities of salt water with their crude oil.

The petroleum industry's solution to the restriction of surface disposal was to initiate injection of brines into suitable subsurface strata.

Pollution of streams and potable water resources by industrial wastes including brines presents a great hazard. Every year there is an increase in industrial water consumption, and a corresponding rise in fluid waste that must be disposed of.

Liquids, gases, and liquid wastes in reasonable quantities probably can be safely injected into the underground strata, if such operations are responsibly managed with adherence to rigid standards. Deep injection waste disposal is no more than storage in underground space of which little is attainable in some areas and which is exhaustible in most areas (Piper, 1969). These and other problems are reflected in the following descriptions of the policies in effect and the existing installations and proposed projects in Illinois.

SUBSURFACE WASTE DISPOSAL

Before any construction can begin on storage in subsurface strata, a permit must be secured from the Illinois Environmental Protection Agency. Before the issuance of a permit for a particular facility, the Board requires the submission of such plans, specifications and other information as it deems relevant and necessary. The general procedure followed is that the interested industry prepares a comprehensive feasibility report and submits it to the Board's Technical Secretary for review and comment, and if satisfactory, receives tentative approval subject to the submission of final construction documents for the proposed test wells prior to drilling. The following basic policies have been adopted:

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

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(1) All zones to be considered for disposal must contain brine waters having over 10,000 mg/l total dissolved solids. This equates to a 1 percent solution of total dissolved solids. Fresh water is now defined as water of 10,000 mg/l or less total dissolved solids. A figure of 5000 mg/l or less had been used until recently to define fresh water, but this was revised upward to preserve ground waters that may be usable if and when current experimental methods of desalination are made practical for the production of potable water from brackish waters.

(2) There must be an effective and adequate impermeable barrier overlying the disposal zone to prevent upward migration of either the wastes or displaced brine waters into fresh water zones.

(3) The well bore must be double cased and the annular space grouted to a point 200 feet below the lowest fresh water zone. The outer casing is to be set into the next lower suitable rock barrier.

(4) The industry must indicate the character and volume of waters to be injected into the deep well. Compatibility of the wastes with the formation fluids must be indicated.

(5) Operational injection pressures to be used must be indicated in the plan documents. Injection pressures that cause fracturing of the rock formations in the injection zone have not been permitted.

(6) Detailed information about the proposed surface injection equipment must be provided as a part of the plan documents.

(7) The industry is required as a condition of the permit to submit daily injection report records each month to the Illinois Environmental Protection Agency. These operating reports must include the character and volume of the waste and show the injection pressures.

(8) Currently the Illinois Environmental Protection Agency is reviewing the necessity for requiring the installation of observation wells to detect the escape of any fluids from the disposal zone.

The disposal of industrial wastes in deep wells is considered relatively new to Illinois. It is realized that pollution of any underground potable or fresh waters will undoubtedly represent long-term damage. It is believed and hoped that the procedures governing the installation and operation of deep disposal wells are conservative. If there is error in engineering and administrative judgment, it is hoped that it will be toward the conservative side of the scale so that the critical natural resource of underground water is protected for present and future use.

The primary desirable characteristic of a subsurface disposal reservoir is that it be deep enough to preclude any possibility of contamination of potable ground-water supplies. Second, the disposal reservoir must be deep enough to preclude any adverse effect on oil or gas production in the area, and third, it must be a suitable geologic formation. To be suitable, the subsurface strata must have sufficient porosity and permeability to accept fluid wastes at reasonable pressures and contain them indefinitely. The selected strata must have a caprock that is sufficiently impermeable vertically to prevent upward migration of injected fluid. Sandstone, limestone, and dolomite are the basic lithologies most commonly considered as potential disposal reservoirs in Illinois.

The most desirable horizon is a sandstone, containing salt water (minimum of 10,000 ppm of dissolved solids), with high porosity and permeability. Also there are several limestone and dolomite reservoirs in Illinois that contain great volumes of salt water and can be considered for storage or disposal areas. The usefulness of these types of sedimentary formations varies since their porosity and permeability depend mainly on fractured and developed solution channels.

From well cores of such formations, essential laboratory studies are conducted defining the rate of fluid movement, porosity, and permeability of the rock and the pressure distribution within the salt water aquifer.

Plugging of the injection horizon is the most serious cause of damage to a fluid injection system and results from the forming of an impermeable deposit on the well bore or plugging in the formation itself. In either case, the plugging may result from a number of causes:

(1) Injection of fluid containing suspended solids which are often chemical precipitates.

(2) Accumulation of corrosion products.

(3) Precipitation within the formation as a result of incompatibility of the injected fluid with the connate water of the formation.

(4) Injection of insufficiently treated water resulting in bacteriological plugging.

(5) Swelling of mineral constituents in the formation.

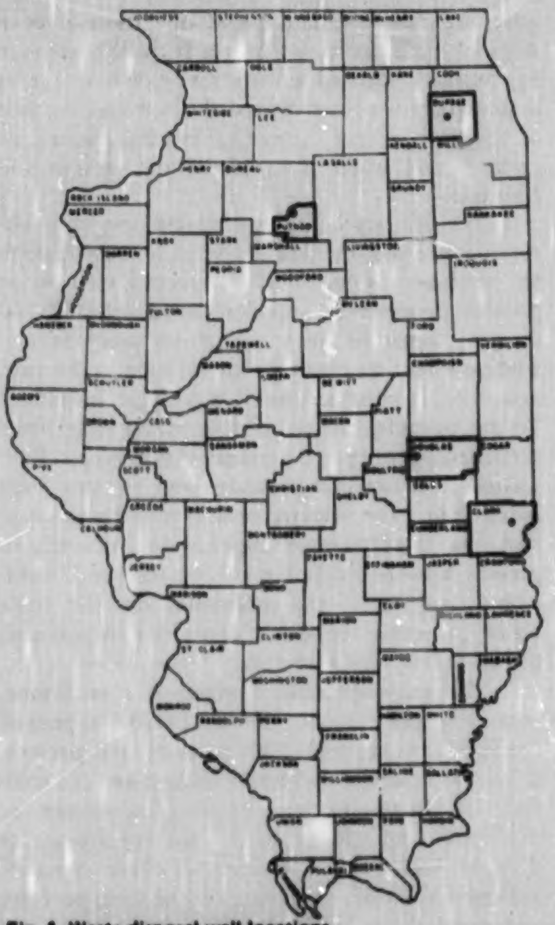


Fig. 1. Waste disposal well locations.

In most cases the waste product, prior to injection, will require treatment such as filtration to remove any suspended solids that might deposit on the face of the formation. It may require treatment by additives to stabilize the solution or to prevent excessive equipment corrosion.

Laboratory tests on core samples of the formation will give information on the maximum particle size of the suspended solids that can be passed in the filtration process.

The first deep disposal well in Illinois was placed in operation in November 1965. Since then three other facilities have been placed in operation.

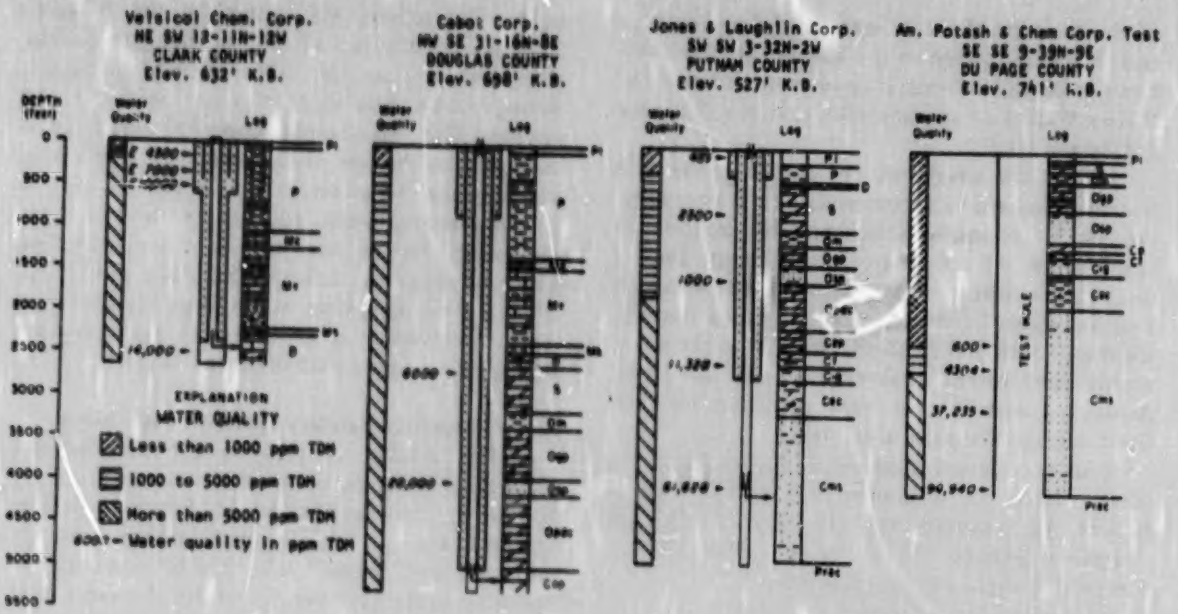
To date there have been four industrial waste disposal wells in Illinois, one in Clark County, two in Douglas County, and one in Putnam County (Figure 1). Variation in conditions in Illinois is illustrated by these cases of disposal wells that have been authorized by the Sanitary Water Board (Bergstrom, 1968).

The well in Clark County disposes 55 to 65 gallons per minute (gpm) of alkaline solution with about 65,000 to 100,000 mg/l dissolved minerals into creviced Devonian age limestone at a depth of about 2500 feet. Potable water occurs in the glacial drift and the upper part of the Pennsylvanian rocks, but below a depth of a few hundred feet, mineralization of water increases rather sharply with depth. Upward migration of alkaline waste water would probably be prevented by shales in the Mississippian and Pennsylvanian rocks. The water at 2500 feet had total dissolved minerals of more than 14,000 mg/l.

A somewhat deeper disposal well now in operation in Douglas County was designed for injection of about 35,000 gallons per day (gpd) of hydrochloric acid into creviced Potosi Dolomite of Cambrian age at a depth of about 5000 feet. Originally designed for injection of wastes into the St. Peter Sandstone, the well was drilled deeper when the permeability of the St. Peter Sandstone was found to be too low. Substantial shale sections occur above the disposal zone, and the more permeable formations contain water with more than 5000 mg/l dissolved minerals below the lower Pennsylvanian (Figure 2). The water at 5000 feet had total dissolved solids of more than 20,000 mg/l. A second waste disposal well having about the same depth and construction features as the first Douglas County well, Figure 3, has been drilled and placed in operation in the vicinity of the first Douglas County well.

The well in Putnam County is for the disposal of about 100,000 gpd of hydrochloric and chromic acid from a steel mill. It is in the area where the St. Peter Sandstone contains usable water, but the Ironton-Galesville and Mt. Simon Sandstones contain brackish to saline water. Injection of wastes is into a zone of the Mt. Simon Sandstone at a depth of about 4000 feet. The low permeability of shaly beds in the Eau Claire Formation and the large reservoir capacity of the Mt. Simon Sandstone will prevent the acid waste from moving upward into the zone of potable water.

Conditions in the northeastern part of Illinois where potable ground water extends into the upper part of the Mt. Simon Sandstone are illustrated by a test hole recently drilled in DuPage County. The well penetrated the entire Mt. Simon Sandstone (2200 feet thick) and reached the Precambrian crystalline basement rocks at a depth of about 4000 feet. Potable water extended to a depth of about 2300 feet, or 500 feet into the Mt. Simon. Below this depth the mineralization of the water gradually increased to more than 90,000 mg/l at the base of the Mt. Simon. The 1700 feet of Mt. Simon that contain nonpotable water consist mainly of sandstone, with only a few thin shaly zones. It is questionable whether there are impermeable shaly zones in the lower Mt. Simon Sandstone with


Velsicol Chem. Corp.
NE SW 12-11N-12W
CLARK COUNTY
Elev. 632' K.B.
Cabot Corp.
NW SE 31-16N-8E
DOUGLAS COUNTY
Elev. 698' K.B.
Jones & Laughlin Corp.
SW SW 3-32N-2W
PUTNAM COUNTY
Elev. 527' K.B.
Am. Potash & Chem Corp. Test
SE SE 9-39N-9E
DU PAGE COUNTY
Elev. 741' K.B.
DEPTH (feet)
Water Quality
Log
TEST HOLE
EXPLANATION
WATER QUALITY
Less than 1000 ppm TDM
1000 to 5000 ppm TDM
More than 5000 ppm TDM
6000 - Water quality in ppm TDM

From Robert E. Bergstrom (1968)

K.B. = Kelly Bushing
E = estimated
ppm tdm = parts per million total dissolved minerals
Pl = Pleistocene
P = Pennsylvanian

M = Mississippian
Mc = Chesterian
Mv = Valmeyeran
Mk = Kinderhookian
D = Devonian
S = Silurian

O = Ordovician
Om = Maquoketa
Ogp = Galena-Platteville
Osp = St. Peter
Opdc = Prairie du Chien
C = Cambrian

Cep = Eminence-Potosi
Cf = Franconia
Cig = Ironton-Galesville
Cec = Eau Claire
Cms = Mt. Simon
Prec = Precambrian

Fig. 2. Construction details and formations penetrated by disposal wells.

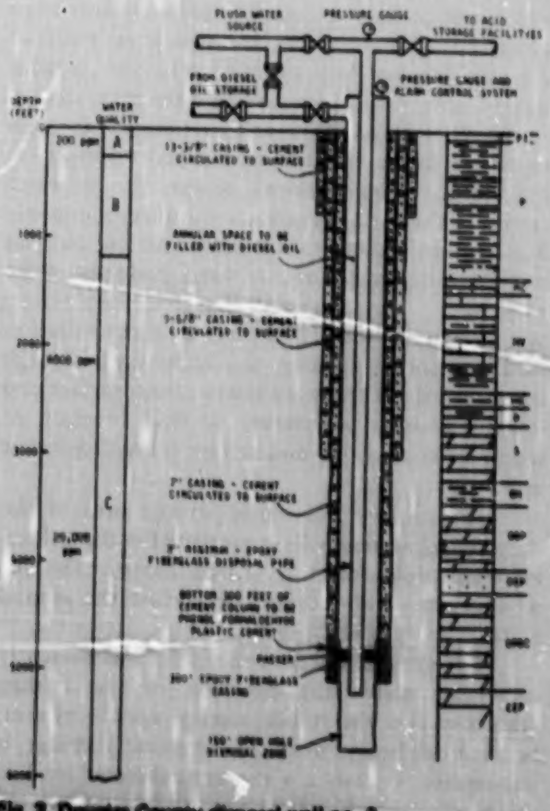

FLUSH WATER SOURCE
PRESSURE GAUGE
TO ACID STORAGE FACILITIES
FROM DIESEL OIL STORAGE
PRESSURE GAUGE AND ALARM CONTROL SYSTEM
DEPTH (FEET)
WATER QUALITY
200 ppm
A
B
C
6000 ppm
25,000 ppm
13-3/8" CASING - CEMENT CIRCULATED TO SURFACE
ANNULAR SPACE TO BE FILLED WITH DIESEL OIL
9-5/8" CASING - CEMENT CIRCULATED TO SURFACE
7" CASING - CEMENT CIRCULATED TO SURFACE
PACKER
300' EPOXY FIBERGLASS CASING
150' OPEN HOLE DISPOSAL ZONE

Fig. 3. Douglas County disposal well no. 2.

sufficient thickness to prevent any wastes from moving upward into the zone of potable water. This test hole has been abandoned.

For all new disposal wells, after completion of drilling and evaluation is made of all available subsurface information (sample descriptions, core descriptions, logs, porosity, and permeability analyses), injection tests are made for a period of up to 30 days. The injection tests are made with filtered and treated water to preserve the injection characteristics of the formation. Data from the injection test will be used to determine the pressure volume relationship of the formation for future injection. In the case of the Putnam County well, calculation of the rate of advance of the interface between the water and the pickle liquor showed that the radius of interface would be about 460 feet in 20 years.

CHICAGO AREA DEEP TUNNEL PROJECT

The early sewer systems in the Chicago area were combined sewers intended to handle both storm water and raw sewage. This practice has continued, for the most part, until the present. The present combined sewer system serves 300 square miles of heavily populated area.

In time of storm, the capacity of the interceptor sewer and treatment system is too small to handle both sewage and storm water. Therefore, during such periods relief is obtained by discharge of the mixture of storm water and raw domestic and industrial sewage to the waterways. The overflows from the combined sewer system enter the Illinois Waterway at some 400 locations (Sheaffer and Zeizel, 1969).

When the overflows are too large for the waterway system to accommodate, it is necessary, on rare occasions, to discharge this mixture of storm water and sewage to Lake Michigan. Such a discharge occurred on August 16, 1968. Although such occasions have been rare (only four times in the last 25 years), they are detrimental to the water supply and recreational activities of the area. Associated with this on many occasions has been flood damage along the waterway.

An economical solution to the problem has been offered – it is known as the deep tunnel project. It combines the (1) City of Chicago underflow concept with the (2) Metropolitan Sanitary District deep tunnel project.

(1) Chicago Underflow Concept

It is proposed to construct a large tunnel under the rivers and canals into which all of the combined sewers in Chicago would discharge. Thus spillages from the combined sewers would not pollute the surface streams but would be directed to the underground tunnel referred to as the "underflow mainstream." The plan calls for about 54 miles of mainstream tunnel, plus approximately 40 miles of branch tunnels. The mainstream tunnel would function as a huge surge tank, taking the overflow which the treatment plants cannot handle during periods of rainfall. After the flow had peaked, the underflow tunnel would be pumped out and sent to Chicago's sewage treatment plants. To connect the combined sewer to the mainstream, tunnel shafts would be dropped down to it at each outflow sewer's point of discharge.

Chicago has started construction on the first underflow sewer which runs from the Chicago River westward paralleling Lawrence Avenue for about 22,100 feet. The tunnel will have two sections (Pikarsky and Keifer, 1967). The first section will be 9300 feet long and 17 feet in diameter, and the second section will be 12,800 feet long and 12 feet in diameter. A branch tunnel 4000 feet long and 12 feet in diameter extending along Harding Avenue and south of Lawrence Avenue is proposed.

Construction is being done by a tunneling mole that is used to bore through the Niagaran Limestone stratum at a depth of about 200 feet below the ground surface.

Ground water is to be protected by lining or otherwise sealing the tunnel in any sections where there is leakage. The tunnel will be about 125 feet below the present water level in the Niagaran Limestone. There is a possibility that there will be some leakage from the tunnel toward the aquifer during storm periods that might surcharge the system. This maximum period of surcharge is estimated to be less than three days and would permit a small flow toward the aquifer.

Monitoring wells, equipped with water-level measuring devices and provisions for collecting water samples, are to be placed along the tunnel. This monitoring system will indicate any change in aquifer pressure or in water quality in the vicinity of the tunnel that would indicate leakage.

(2) Metropolitan Sanitary District Deep Tunnel

The general concept of the Metropolitan Sanitary District deep tunnel system, as presently proposed, combines the City of Chicago underflow concept with an underground storage concept (Sheaffer and Zeizel, 1969). The tunnels designed for flow under pressure, to utilize the large head available, will conduct the overflow water to a central mined storage reservoir, some 830 feet below the land surface. The mined storage reservoir, made up of large unlined chambers in the Galena-Platteville dolomite, will consist of two sections, a settling chamber and the main storage reservoir.

Sewage will first flow into a settling chamber, which will be large enough to contain runoff from small and medium storms, and will retain much of the solid loads of large storm runoffs. The partially treated sewage will then flow into the main storage reservoir, from where it will be pumped through reversible pump turbines to a diked reservoir on the surface using off-peak power. Storm water stored in the surface reservoir will further improve in quality by sedimentation and oxidation, and will then be fully treated and released gradually to the waterways. It is estimated that the deep tunnel system will eliminate 99.5 percent of the pollution load presently reaching the waterways through storm overflows from the sewers. Both surface and lower reservoirs will serve the dual function of storm water retention and storage for hydroelectric generation.

The tunnels and mined storage area of the deep tunnel system will be excavated in the Galena-Platteville dolomite stratum that underlies the area at a depth of about 800 feet below the ground surface.

The ground water in this aquifer is presently somewhat above the elevation of the settling chambers and the mined storage area. However, because of heavy usage, the natural recharge is inadequate to maintain the ground-water level in the aquifer, which is falling generally at an average rate of about 13 feet per year throughout the area, and soon will be below the storage area elevation.

To adequately protect the water levels in the aquifer they must be maintained above the tunnels and mined storage area. This can be done in one of two ways, (1) by control of ground-water pumping, or (2) by artificial recharge of the aquifer. It is believed more conservative at present to recharge the aquifer.

The feasibility of aquifer recharge has been based on extensive ground-water investigations, including an electric analog computer study and field drilling, seismic surveys, well geophysical logging, and aquifer pumping tests.

The tunnels and mined storage area will not be allowed to become pressurized above the ground-water pressure.

ARTIFICIAL RECHARGE OF THE CAMBRIAN-ORDOVICIAN AQUIFER WITH TREATED SEWAGE EFFLUENT

Artificial recharge has been suggested as a remedial measure for some of the water-supply problems of the Chicago metropolitan area (Sheaffer and Zeizel, 1966; McDonald and Sasman, 1967; and Jones and Heil, 1967). Since the aquifer is deeply buried it will be necessary to recharge the aquifer through wells.

The source of water considered for artificial recharge is sewage effluent (reclaimed water) from tertiary treatment plants. Culp (1969) states that reclaimed water represents a large potential source of water.

A major problem in well artificial recharge operations is maintaining injection capacity. Clogging of injection wells has been reported by many investigators. Although the recharge water may be classified as of drinking quality, further treatment may be necessary or methods of well rehabilitation may be needed to maintain injection capacity. In addition, the effectiveness of the filtering action of consolidated sandstones needs to be established.

The State Water Survey has planned a study to reproduce the processes occurring in injection wells under controlled conditions in the laboratory. The object of this research is to study the feasibility of recharging effluent from a tertiary treatment plant into the deep sandstone aquifer in northeastern Illinois, and to investigate methods of further treatment of tertiary treated sewage effluent so that it can be used successfully to recharge the aquifer system.

Upon completion of this initial research it is proposed that a field research project consisting of a deep sandstone recharge well with four water level and sampling wells be constructed in the Chicago metropolitan area and operated together with the necessary treatment facilities.

UNDERGROUND GAS STORAGE

Space heating in homes and other buildings consumes large amounts of gas. Because of the seasonal fluctuations in the demand for gas for space heating, the total gas demand generally varies considerably from summer to winter.

To make better use of the gas pipelines from the gas fields to the users through the year, the gas distributors have acquired more heating customers than the pipelines can supply in the middle of winter. Then, any deficiency in gas supply is made up by using gas stored underground during summer months.

The first practical use of underground gas storage in Illinois was by Mississippi River Fuel Corporation at Waterloo in 1950 (Bushbach and Bond, 1967). In 1952, Natural Gas Pipeline and Panhandle Eastern Pipeline Companies started their large projects at Herscher and Waverly, respectively. Since then, the number of projects and their capacities have grown continuously. At the present time there are 24 underground gas storage projects, and Illinois ranks fifth in total reservoir capacity among States that have underground gas storage. Pennsylvania, Michigan, Ohio, and West Virginia each have 1½ to 2 times the capacity of Illinois (Martinson, et al., 1966). Illinois has more potential aquifer storage capacity than any other State.

To store natural gas underground the following conditions are needed: (1) rock layers with sufficient permeability and porosity to accept and hold gas, (2) an impermeable caprock overlying the storage rock to prevent upward migration of gas, and (3) a geologic trap to keep the gas from moving in a horizontal direction. This trap may be a dome or closed anticline caused by gentle upward arching of the strata, a stratigraphic trap caused by updip gradation of the reservoir rock from sandstone to shale, or a trap caused by faulting that seals the updip side of the reservoir by replacement of an impermeable bed adjacent to the reservoir.

The porous storage rock in a geologic trap under the caprock is called a reservoir. This reservoir may have been filled originally with oil or gas and thus may be a depleted oil or gas reservoir. On the other hand, the reservoir may have been filled originally with water; in this case, it is called a natural aquifer. The water in an aquifer could be fresh or salty. In Illinois fresh water aquifers are not used for gas storage because they are too valuable as sources of water for human consumption.

When gas is injected into an aquifer, water is displaced from the pores of the rock around the injection well. The water and rock around the storage gas bubble is compressed. In a typical storage aquifer roughly half of the space for the injected gas is created by the compression of the solid rock matrix and half is created by the compression of the water in the pores of the rock. Near the storage bubble the fluid pressure in the pores of the rock is the same as it is within the bubble.

The higher the injection pressure, the greater the rate at which the storage bubble is developed. If gas is injected at too high a pressure, the caprock may be fractured. Experience with hydraulic fracturing of oil and gas producing wells to increase production of these wells shows that sand-face pressures from about 0.7 to 1.0 psi per foot of depth are required to cause fracturing. In gas storage aquifers, injection pressures of approximately 0.55 psi per foot are often used.

Besides pressure per foot of depth, the difference between the injection pressure and the initial fluid pressure in the aquifer must also be considered. In the early stages of the development of the bubble, this difference is usually held at about 100 psi. If experience shows that this causes no leakage problems, the pressure difference is then increased to 200 psi or more but should not exceed 400 psi except in special cases where extra control precautions can be taken.

Pipeline companies and other companies subject to the regulations of the Federal Power Commission must satisfy the requirements of that Commission with respect to any proposed underground gas storage project. Public utilities operating in Illinois are subject to the "Public Utilities Act" (Illinois Revised Statutes, 1965, chapter 111 2/3). Under Section 55 of this act, the Illinois Commerce Commission is directed to issue an order authorizing a new facility (such as an underground gas storage project) after it has found that the new facility is necessary.

The Natural Gas Storage Act (Illinois Revised Statutes, 1965, chapter 104, sections 104-112) gives storage companies the right to use private property for gas storage purposes in the manner provided for by the law of eminent domain. According to the act, before the right of condemnation can be exercised, the corporation must receive an order from the Illinois Commerce Commission approving the proposed storage project. The Commerce Commission cannot issue such an order unless it finds that the proposed storage (1) will be confined to strata lying more than 500 feet below the surface, (2) will not injure any water resources, and (3) will involve no condemnation of any interest in any geological stratum containing oil, gas, or coal in commercial quantities within the area of the proposed storage.

In addition, gas storage companies that operate in Illinois are subject to certain rules and regulations of the Illinois Department of Mines and Minerals and the Illinois Environmental Protection Agency. Each well that is drilled requires a permit from the Department of Mines and Minerals. Furthermore, the storage company must furnish evidence to the Illinois Environmental Protection Agency that the proposed storage project will not result in the pollution of potable water.

Observation wells are required by the Illinois Commerce Commission for measuring pressures within the gas bubble and for measuring changes in water pressures in all directions from the bubble in order to detect any possible gas leakage. Records of these daily observations are submitted monthly to the Commerce Commission and the Illinois State Water Survey for study.

WATERFLOOD OPERATIONS

Waterflooding has become an effective and economical means of stimulating oil production and is essential to the oil industry of the Illinois Basin. Secondary recovery by waterflooding accounted for 73.4 percent of the total oil production in Illinois during 1968 (Lawry, 1969). In 1968 there were 880 active projects in Illinois with 13,107 water injection wells that injected 518,581,000 barrels of water (2581 million gallons).

Most of the water used in waterflooding is brine that originates from the same formations that produce oil. Thus, waterflooding presents very few problems in contaminating the ground-water aquifer as it replaces oil and water that has been withdrawn.

Good well construction is controlled by a permit and inspection system administered by the Illinois Department of Mines and Minerals.

SUMMARY

Great caution must be exercised in the selection of formations to receive liquids and gases and liquid wastes for storage underground. Confining formations to prevent migration of wastes and stored material to the ground-water aquifer must be assured before injection of liquids into permeable and porous formations is permitted. Adequate protection of the potable ground-water reservoirs must be established and maintained at all times.

This is done in Illinois through an adequate permit and inspection system requiring a high standard of facility design. These designs for any given project must satisfy the requirements of the Federal Power Commission, the Illinois Department of Mines and Minerals, the Illinois Environmental Protection Agency, or the Illinois Commerce Commission, depending on the circumstances.

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DISCUSSION

The following questions were answered by H. F. Smith after delivering his talk entitled "Subsurface Storage and Disposal in Illinois."

Q. *Who is going to pay for the artificial recharge program—the public, the beneficiaries, or others?*

A. The artificial recharge program will be paid for by the public—in other words, the people who are going to use the water. In this case the public would be the beneficiaries.

Q. *What is the storage capacity in days of storm water runoff systems?*

A. The storage design was for 2 inches of runoff.

Q. *Assuming that fluids break through to the surface, or to aquifers, what do you do for an encore—apologize, pump into the stream, rapidly build a treatment plant, change the permit form, or what?*

A. This problem was encountered in the early beginnings at the Herscher Field not long after it was put in operation. They had too few injection wells so it was decided to increase the pressures, and they probably got a fracturing pressure with some cement that wasn't as good as it could have been. They had some migration of gas from the lower zones up into an upper aquifer. In fact, two or three farmers had free gas for awhile which they didn't appreciate. They were paid something for their inconvenience and I think everyone was satisfied with the final results of more wells, lower injection pressures and better well construction. The same could apply to wastes, as long as they aren't too toxic. The wastes being disposed of at present in Illinois are the kind that can be diluted with water.

Q. *This one's a little allied. Michigan has had a couple of bad gas leaks in private wells. Has Illinois had any problems and how did they correct the leaks? How much damage did brine leakage do to fresh-water aquifers, and was it corrected?*

A. Well, I just mentioned a little about the gas leaks. We have had two shallow aquifers go bad by brine intrusion. The correction was made by moving five miles to another well field. I don't think it has actually been decided who is going to pay the cost of the five miles of pipeline.

Q. *You described four disposal systems in Illinois. Have you had other applications in Illinois—how many, and how many of those have been accepted to date?*

A. The IEPA has requests for two additional permits for disposal wells. To date, permits have not been issued for either well.

Q. *Regarding the DuPage County Company that was unwilling to give a definite analysis of their effluents for underground waste disposal, who permitted their discharge to surface water in their present system? Is it now being monitored, and what standards must they comply with—what penalties must they face?*

A. The Company is now using an oxidation pond, and there are suspicions that it has leaked. They have monitored wells as much as 2500 feet from the pond. Where contamination was noted, the Company ran a pipeline from the city supply to the affected wells.

Q. *Your printed summary noted plugging problems related to both the well bore and the formation. Bill Tucker noted a similar problem and possible* *solution by remedial acidizing. Could you expand on both the problem and possible solutions?*

A. I did not get into this because of time, but we are having a discussion in Illinois on what is a maximum size particulate that can be put into these aquifers. Some of the consultants want to use a filter that will filter down to about 15 microns. We think perhaps a 5 micron filter will be necessary. This is being substantiated by field data. The effluent in the well in Putnam County which is from a steel mill's waste, is filtered through diatomaceous earth filters. Their particulate is reduced to between 10 and 15 microns. I understand that their injection pressures have continued to rise, and they believe that within the next six months they are going to have to rehabilitate the well. I am not familiar with how they intend to do it, but most rehabilitation of the deep sandstone in our area is done by some type of explosive such as primacord, to clean off the well bore. They are injecting a pickling acid which has a pH of about 1½ so they have a real strong acid in the well. I am not familiar with an acid they could use that would help them more. They may depend on shooting and then cleaning out for this particular rehabilitation.

Q. *How can an injection well be justified under Section 12 of the Illinois Environmental Protection Act?*

A. The IEPA tells me that under this particular Section they are not able, at this time, to prohibit the construction of an injection well if it is properly constructed and the effluent is acceptable.

Q. *What is the rationale of thinking regarding changing criteria for salinity of injection horizons from 5,000 at present to 20,000 milligrams per liter in the future? Will desalting perhaps make water usable and needed in the future?*

A. Yes, we think that desalting can make brackish water usable economically. Five years ago we thought that 5,000 ppm of salinity would be a maximum for conversion but we are now of the opinion that with certain types of new procedures and processes, water with 10,000 ppm and perhaps 20,000 ppm of salinity can be demineralized in an economical fashion. We are raising our sights to that figure.

Q. *What is your opinion of a bill recently introduced in Washington proposing that the federal government regulate all subsurface injections?*

A. I believe I'll pass that for the time being.

Q. *Has the storage of gas in sandstone domes in Illinois had any effect on local deep aquifer systems regarding quality, pressure, flow, etc.?*

A. None that we know of. We have had observation wells from about 2,000 feet up to 20 miles from these domes, and we are unable to see that the gas pressure has had any great effect on the aquifer system. In fact, it has had less effect than we really thought it would have.

Q. *Regarding increasing pressure, how much differential sheer will you permit between formation and the casing?*

A. I don't have that answer right at hand.

Q. *Are periodic, complete chemical analyses, including base metals, required for all injection fluids?*

A. Yes. We originally asked for daily samples, but at the present they are collecting composite samples over a period of two or three days.

Q. *What specific records are required from industrial disposal well operators?*

A. The records required are: an analysis of the fluid injected, the rate, the injection pressure, and annulus pressure.

Q. *Have there been any failures or problems with any of the storage or disposal systems, beyond the ones you mentioned in your talk?*

A. I do not know of any failures that have occurred other than those mentioned. The systems have been designed, I think, rather well. The IEPA has insisted and, of course, the former Department of Health who formally issued permits, insisted that the companies use good design and follow a prescribed method of monitoring, and they have done real well. One or two gas wells went bad in the early beginnings. Since they have limited the pressures on all wells so there is no fracturing of the formation or any possible disturbance of the cement bond, the wells have worked real well.

Feasibility of Recharging Treated Sewage Effluent into a Deep Sandstone Aquifer[a]

by Richard J. Schicht[b]

ABSTRACT

Artificial recharge with tertiary treated sewage effluent has been suggested as one remedial measure for projected ground-water deficits in the Chicago region. A deep sandstone aquifer, an important source of ground water in the region, offers the best opportunity for artificial recharge. Recharge will be through wells since the aquifer is deeply buried. Expected problems in maintaining well injection capacity were studied by recharging treated effluent through formation cores of the sandstone. Some success was had in maintaining recharge rates at constant heads for several days.

INTRODUCTION

The Illinois State Water Survey is engaged in a comprehensive water-supply study of the metropolitan Chicago region (northeastern Illinois) (Figure 1), an area of about 4000 square miles with a population of about 7.0 million. It is expected that results of this study will aid in determining the State's strategy for meeting the demands for water for the region to the year 2020. The Water Survey will investigate alternatives and possibilities from all sources and the economics of each. It is expected that the study will include use of desalted water, artificial recharge, reuse, diversion of surface water, and importation of ground water from outside of the region.

The importance of ground water in the area is emphasized by the population dependent upon ground water as a source of water. Census figures for the 6-county area are given below.

	U. S. Census Count for 1970
6-County Region	6,978,947
Cook County	5,492,369
Suburban Cook	2,125,412
Chicago	3,366,957
Du Page County	491,882
Kane County	251,005
Lake County	382,638
McHenry County	111,555
Will County	249,498

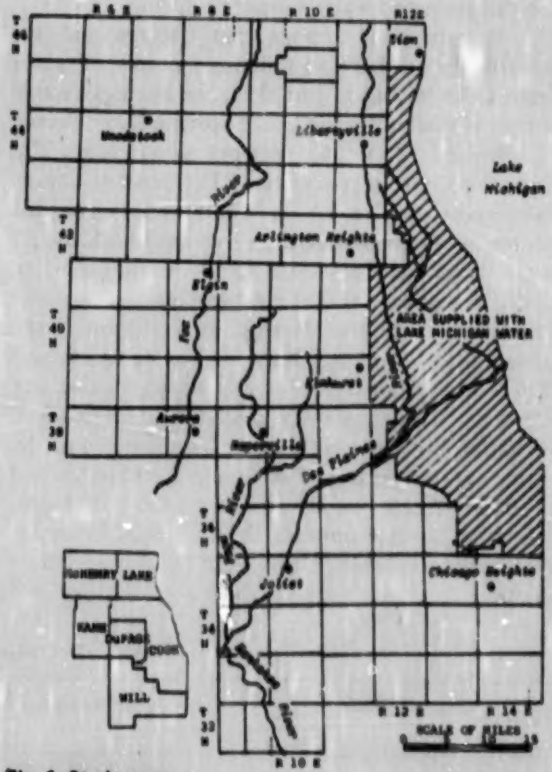
R 6 E
R 8 E
R 10 E
R12E
T 46 N
T 44 N
T 42 N
T 40 N
T 38 N
T 36 N
T 34 N
T 32 N
Zion
Woodstock
Libertyville
Lake Michigan
Arlington Heights
Elgin
Fox
AREA SUPPLIED WITH LAKE MICHIGAN WATER
Elmhurst
Aurora
Naperville
Des Plaines
Joliet
Chicago Heights
McHENRY
LAKE
KANE
DuPAGE
COOK
WILL
R 12 E
R 14 E
SCALE OF MILES
0
10
15
R 10 E

Fig. 1. Study area.

It is estimated that about 25 percent of the region's total population—this includes the population of most of Du Page, Kane, McHenry, and Will Counties, over one-half of Lake County and about one-fourth of Suburban Cook County—are presently dependent upon ground water as a source of water. Population and percent of population in the region dependent upon ground water from work by Schicht and Moench (1971) for 1980, 2000, and 2020 are given below.

		Population and Percent of Population Dependent Upon Ground Water	
Year	*Projected Population*	*Population*	*Percent*
1980	8,258,390	2,389,160	28.9
2000	10,867,805	4,363,620	40.1
2020	14,641,950	7,526,290	51.4

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

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The report by Schicht and Moench (1971) stated that the total potable ground water in the 6-county area was greater than the total projected demand by the year 2020. To meet demand in some areas, however, importation of ground water or surface water or development of alternative sources locally may be necessary. Artificial recharge is strongly being considered as a remedial measure for the projected water-supply problems.

It may seem strange that Chicago and her suburbs do not have an unlimited supply of water from Lake Michigan. But the Lake Michigan water supply is limited by the U. S. Supreme Court decree of 1966 to 3200 cubic feet per second (cfs). The Supreme Court decree states: "The State of Illinois may make application for a modification of this decree so as to permit the diversion of additional water from Lake Michigan for domestic use when and if it appears that the reasonable needs of the Northeastern Illinois Metropolitan Region (comprising Cook, Du Page, Kane, Lake, McHenry, and Will Counties) for water for such use cannot be met from the water resources available to the region, including both ground and surface water and the water authorized by act of Congress and permitted by this decree to be diverted from Lake Michigan, and if it further appears that all feasible means reasonably available to the State of Illinois and its municipalities, political subdivisions, agencies and instrumentalities have been employed to improve the water quality of the Sanitary and Ship Canal and to conserve and manage the water resources of the region and the use of water therein in accordance with the best modern scientific knowledge and engineering practice."

PREVIOUS ARTIFICIAL RECHARGE INVESTIGATIONS

Artificial recharge into two aquifer systems, referred to as the shallow aquifers and the deep sandstone aquifer, have been considered. Generalized aquifer descriptions are given in Table 1). Recharge into the shallow aquifers (shallow sands and gravels and shallow dolomites) has been discussed in the "Water Resources in Northeastern Illinois: Planning Its Use," Northeastern Illinois Metropolitan Area Planning Commission Technical Report No. 4. The sources of water for artificial recharge considered in the report were high flow in surface streams, water that has been used for cooling, certain industrial waste waters, and treated domestic sewage. The pit method was considered mainly because of the experience and success with the pit recharge operation at Peoria, Illinois (Suter and Harmeson, 1960). Areas where the pit method of artificial recharge is potentially favorable were determined for the planning commission report based on data from the Illinois State Geological and

Table 1. Generalized Aquifer Descriptions

Geologic Units	*Thickness (feet)*	*Water Yielding Properties*
Glacial Drift[1]	0-400+	Yields of wells variable, some well yields greater than 1000 gpm.
Silurian Dolomite[1]	0-400+	Yields of wells variable, some well yields greater than 1000 gpm.
Maquoketa Shale	0-250	Generally not water yielding, acts as barrier between shallow and deep aquifers.
Galena-Platteville Dolomite[2]	150-350	Water yielding where not capped by shales.
Glenwood-St. Peter Sandstone[2]	75-650	Estimated transmissivity 15 percent that of Cambrian-Ordovician aquifer.
Prairie Du Chien, Trempealeau Dolomite, and Franconia Formations[2]	45-790	Estimated transmissivity 35 percent that of Cambrian-Ordovician aquifer.
Ironton-Galesville Sandstone[2]	103-275	Estimated transmissivity 50 percent that of Cambrian-Ordovician aquifer.
Eau Claire Shale	235-450	Generally not water yielding, acts as barrier between Ironton-Galesville and Mt. Simon.
Eau Claire and Mt. Simon Sandstones	2000±	Moderate amounts of water, permeability between that of Glenwood-St. Peter and Ironton-Galesville, water quality problem with depth.

[1] Glacial drift and shallow dolomite are referred to as the shallow aquifers.
[2] Collectively referred to as Cambrian-Ordovician or deep sandstone aquifer.

Water Surveys. These areas were limited to reaches of major streams in the region. It was estimated that a potential of 121 million gallons per day (mgd) could be recharged. The aquifers outlined by the Planning Commission as favorable for artificial recharge are in areas for the most part where ground-water deficits are not expected to occur until after 2020.

McDonald and Sasman (1967) described a study made for Park Forest-Chicago Heights that indicated that artificial recharge to the Silurian dolomite aquifer, the source of water supply in the area, is feasible.

They also described five existing artificial recharge operations utilizing recharge wells. At all five sites water circulating through closed cooling systems is recharged. One installation withdraws water from the deep sandstone aquifer and recharges a shallower sandstone at an average rate of 335,000 gallons per day (gpd). The other four installations withdraw water from and recharge water to the shallow dolomite at average rates ranging from 25,000 to 395,000 gpd.

THE DEEP SANDSTONE AQUIFER

The heavily pumped Cambrian-Ordovician or deep sandstone aquifer, described by Suter et al. (1959) is presently being considered as offering the best opportunity for artificial recharge in the Chicago region.

The deep sandstone aquifer consists in descending order of the Galena-Platteville dolomite, Glenwood-St. Peter sandstone, and Prairie du Chien Series of Ordovician age; and the Trempealeau dolomite, Franconia Formation, and Ironton-Galesville sandstone of Cambrian age. The sequence, structure, and general characteristics of these rocks are shown in Figure 2. The deep sandstone aquifer is separated from the Mt. Simon aquifer by shale beds of the Eau Claire Formation. The Maquoketa Formation above the Galena-Platteville dolomite acts as a barrier between the shallow dolomite and deeper aquifers, and confines the water in the deeper aquifers under artesian pressure. Available data indicate that on a regional basis the entire sequence of strata, from the top of the Galena-Platteville to the top of the shale beds of the Eau Claire Formation, behaves hydraulically as one aquifer.

The Ironton-Galesville sandstone is the most productive formation of the deep sandstone aquifer. The Galena-Platteville dolomite and Prairie du Chien Series generally are not well creviced; the Trempealeau dolomite is locally well creviced. The Glenwood-St. Peter sandstone and Franconia Formation yield small to moderate amounts of water.

The deep sandstone aquifer receives water from overlying glacial deposits mostly in areas of Kane, McHenry, Kendall, Boone, and DeKalb Counties where the Galena-Platteville dolomite is the uppermost bedrock formation below the glacial deposits. This is west of the border of the Maquoketa Formation. Recharge of the glacial deposits occurs from precipitation that falls locally. Vertical leakage of water through the Maquoketa Formation into the deep sandstone aquifer is appreciable under the influence of large differentials in head between shallow deposits and the deep sandstone aquifer.

There are advantages in recharging the deep sandstone aquifer. The aquifer is uniform in permeability and thickness throughout the region, so artificial recharge would benefit many users. The piezometric surface is well defined so that recharge installations can be located to serve specific areas. Continued withdrawals from the aquifer in excess of the practical sustained yield, 46 mgd as estimated by Suter et al. (1959), will create considerable storage volume. The practical sustained yield has been exceeded each year since 1958. It is estimated that water from the deep sandstone will be withdrawn at a rate of 622 mgd by 2020 (the estimated usable water in storage is large, estimated to be 1.6 × 10^{13} gallons).

Since the deep sandstone aquifer is deeply buried it will be necessary to recharge the aquifer through wells. It has been suggested that effluent that meets drinking water quality standards from tertiary treatment plants be used as a source of recharge water. According to Jones and Heil (1967) one of the potential markets for the effluent is for ground-water recharge. They report the interest of Water Commissions in northeastern Illinois in utilizing effluent from tertiary treatment plants for artificial ground-water recharge.

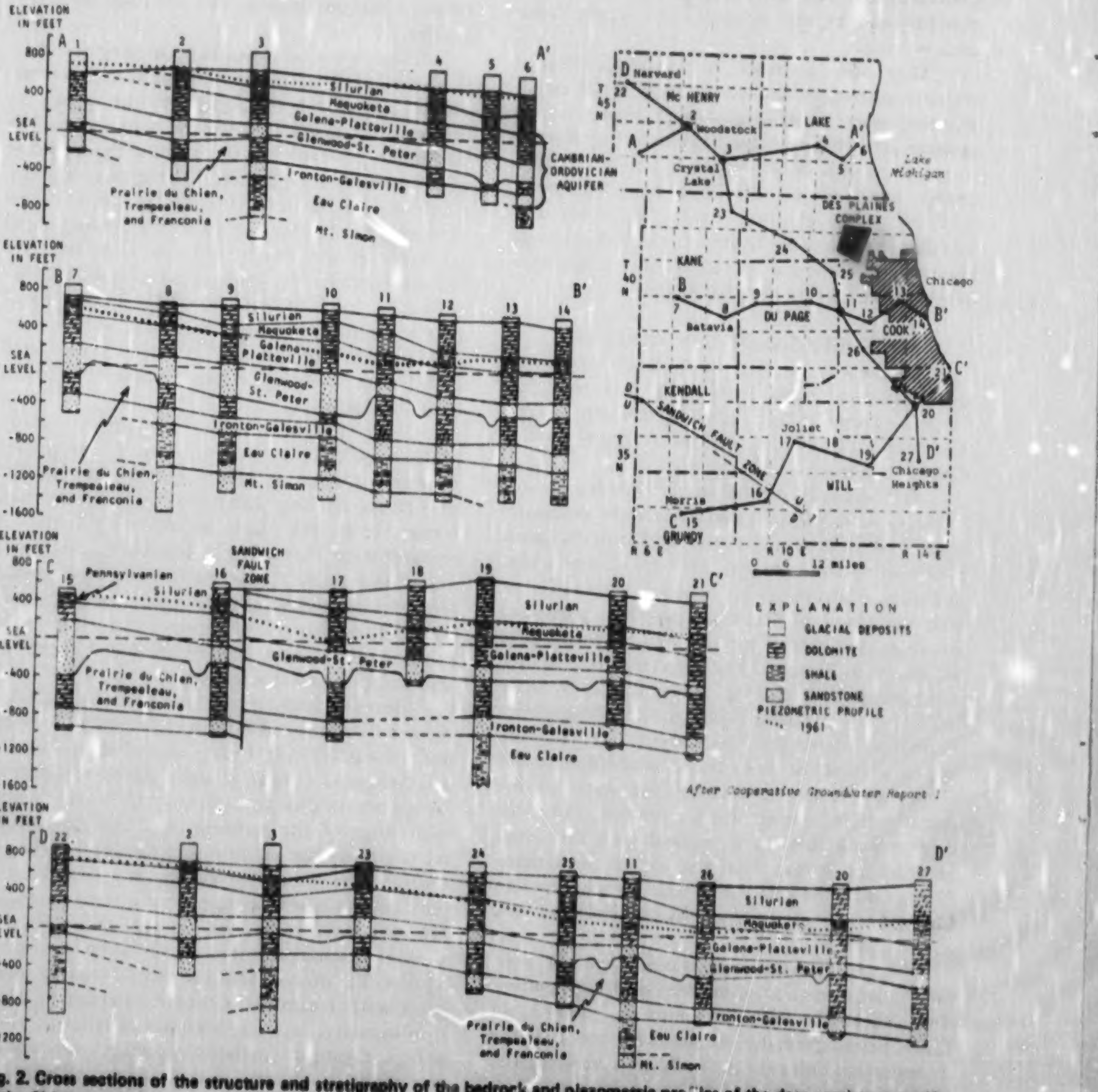
Because clogging of injection wells has been reported by many investigators, including Rebhun and Schwarz (1968), Bruington and Seares (1965), and Sniegocki (1963), it was decided to conduct laboratory studies to acquaint the Water Survey with some of the problems that may arise from recharging sewage effluent into the deep sandstone aquifer. The Water Survey recently completed a pilot project where sewage effluent from a secondary treatment plant was treated and recharged through formation cores of the deep sandstone aquifer. The objectives of the project were to study what water treatment is needed to maintain injection capacity, to study methods of rehabilitation, and to investigate methods of further treatment of secondary or tertiary treated sewage effluent so that it can be successfully used to recharge the aquifer system and meet water quality standards.

The pilot project was described by Smith, Schicht, and Humphreys (1970) and is summarized below.

The new Urbana-Champaign Sanitary District Plant was selected as the initial laboratory site. Since the plant provides only secondary treatment (activated sludge), additional treatment, filtration and chlorination, was provided. It was later found necessary to modify the pH of the effluent.

Three types of filters were used: microstrainers, diatomaceous earth, and rapid sand. All three filters were successful in markedly filtering out suspended solids when operating properly. Two microstrainers were constructed, one with 26 micron cloth, the other with 10 micron cloth. The diatomaceous earth filter was a type used for small swimming pools. A chlorinator was installed ahead of the filters.

The filtered and chlorinated effluent was


ELEVATION IN FEET
800
400
SEA LEVEL
-400
-800
-1200
-1600
A
A'
B
B'
C
C'
D
D'
Silurian
Maquoketa
Galena-Platteville
Glenwood-St. Peter
Ironton-Galesville
Eau Claire
Mt. Simon
Prairie du Chien, Trempealeau, and Franconia
CAMBRIAN-ORDOVICIAN AQUIFER
Pennsylvanian
SANDWICH FAULT ZONE
Harvard
Mc HENRY
Woodstock
LAKE
Crystal Lake
Lake Michigan
DES PLAINES COMPLEX
KANE
Chicago
Batavia
DU PAGE
COOK
KENDALL
SANDWICH FAULT ZONE
Joliet
Chicago Heights
WILL
Morris
GRUNDY
T 45 N
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EXPLANATION
GLACIAL DEPOSITS
DOLOMITE
SHALE
SANDSTONE
PIEZOMETRIC PROFILE 1961
After Cooperative Groundwater Report 1

Fig. 2. Cross sections of the structure and stratigraphy of the bedrock and piezometric profiles of the deep sandstone aquifer in the Chicago region.

injected through a sandstone core used to simulate a well in the deep sandstone aquifer. The Ironton-Galesville sandstone, since it is the most productive formation in the deep sandstone aquifer, was selected for investigation. The cores, 3 inches in diameter, were provided by the Northern Illinois Gas Company, which collected them during a site investigation for underground gas storage. The cores were cut into 3 inch lengths and a 1 inch diameter hole was drilled through their centers.

The cores were placed in a specially designed permeameter. Deionized water was injected to eliminate plugging caused by drilling and cutting and to determine head-discharge relationships. Horizontal permeabilities determined by the Thiem equation indicated that permeabilities of the sandstone cores are comparable to permeabilities of the sandstone determined from aquifer and pumping tests.

The permeameter is designed so that effluent can be injected into the center so that flow is outward through the core similar to an injection well. This will be referred to in subsequent discussions as recharge. Water can also be injected so that flow is from the outside toward the center of the core simulating pumping and will be referred to as backwashing. The rate of recharge was controlled from a constant head tank so that initially the recharge rate into an actual deep sandstone well would be simulated. At first the normal procedure was to recharge for several hours and then backwash with deionized water for a period of 15 to 60 minutes. The purpose of backwashing was to simulate pumping which under field conditions is one method that can be used for well rehabilitation.

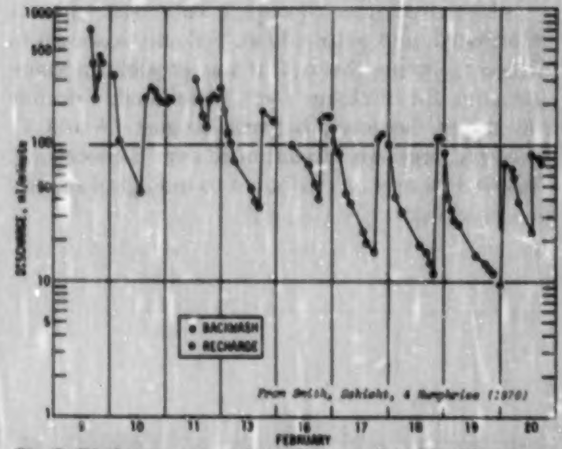
Analyses of the filtered effluent were made to determine ammonium, nitrate, chemical oxygen demand, biochemical oxygen demand, and bacterial counts. Ranges of the above are given below.

NH_4	NO_3	COD	BOD
0.0 to 5.5	19.8 to 57.3	16.8 to 83.3	0 to 8.0

Bacteria plate counts range from 0 to too numerous to count.

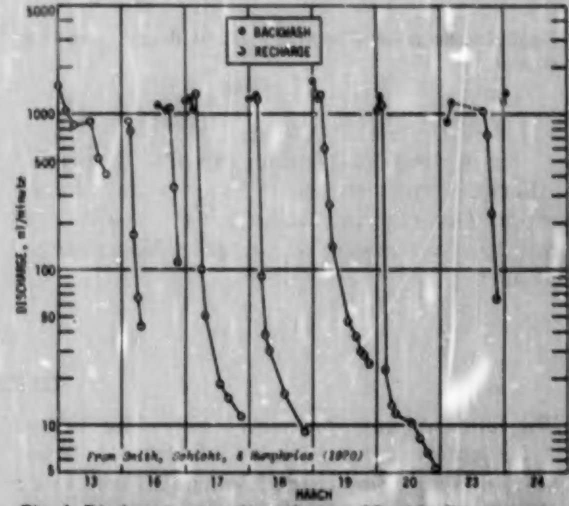
Tests for chlorine residual were made several times daily. A typical chlorine residual would be 7.8 mg/l after filtration, 6.6 mg/l before recharge, and 4.50 mg/l after recharge.

Recharge rates through a core with recharge water filtered by a 10 micron microstrainer and through a core with recharge water filtered by a diatomaceous earth filter are shown in Figures 3 and 4. It is apparent from inspection of the graphs that little success was had in maintaining recharge rates. Some success was had, however, in rehabilitating the cores by backwashing.



From Smith, Schicht, & Humphries (1970)

Fig. 3. Discharge rates through core 6 with 10 micron microstrainer effluent.



From Smith, Schicht, & Humphries (1970)

Fig. 4. Discharge rates through core 10 with diatomaceous earth effluent.

Clogging was attributed to material precipitating out of the recharge water after chlorination. Mineral analysis of the recharge water at several sampling points indicated the precipitate was calcium phosphate and calcium silicate. The addition of chlorine (Sodium Hypochlorate) as a disinfectant was raising the pH, thus decreasing the solubility of the effluent. The pH of the effluent before chlorination was 7.6. The pH after was 8.4. It was decided to maintain a pH no greater than 7.0 by adding sufficient quantities of diluted hydrochloric acid immediately after chlorination.

Discharge rates through a core with filtered, chlorinated, and pH modified effluent is shown in Figure 5. During this trial it was possible to maintain constant discharge rates. Considerable decline was noted, however, between August 14 and 17 when recharge was discontinued over the weekend. This decline may be attributed to biological activity or a precipitate.

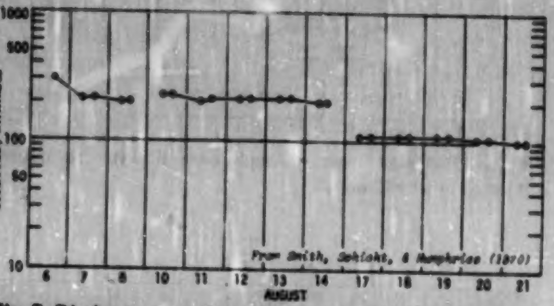


Fig. 6. Discharge rates through core 7 with rapid sand filter effluent.

It is planned to continue this pilot study using effluent from a treatment plant in the Chicago region. One objective of further study will be to maintain constant discharge rates for longer periods of time.

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DISCUSSION

The following questions were answered by Richard J. Schicht after delivering his talk entitled "Feasibility of Recharging Treated Sewage Effluent into a Deep Sandstone Aquifer."

Q. *What are the legal and moral ramifications of diversion of streamflow by well pumping?*

A. In Illinois I'm not familiar with any legal ramifications of diversion of streamflow by well pumping. Most of the diversion of streamflow by induced infiltration, to any appreciable extent, would be along our major streams and has not been great enough to reduce the streamflow any appreciable amount. Now the moral ramification I'm sure is a topic for another session.

Q. *Do you have any cost projections, say a cost per 1000 gallons, to treat and then inject the treated municipal sewage effluent?*

A. The only data I've seen on cost per 1000 gallons to treat sewage is for secondary treatment. As far as I understand, tertiary treatment of sewage effluent is still in the experimental stage, and the cost would not be realistic. However, we plan to make cost estimates of treating and injecting at some stage in the future, but I have no information on this.

Q. *Have you yet attempted to scale your results to actual field conditions? What is the expected injection rate per well?*

A. We try to maintain a realistic injection rate that would be comparable to actual field injection. You can compare about 300 milliliters per minute through the core with several hundred gallons per minute in an actual injection well.

Q. *How do you propose to backwash the aquifer?*

A. We're going to have two strings of pipe in the well, one for injection and one for pumping. The pumping is intended to serve as backwashing.

Q. *Do you know of anyone in the United States that is now recharging a confined aquifer?*

A. Yes, for example there is injection of cooling water in the Chicago region into the deep sandstone aquifer on a small scale.

Q. *Have you compared, or do you plan to compare the direct use of polished effluent versus injecting it into an aquifer?*
A. Yes, we plan to; however, there are probably social reasons for injecting the sewage effluent into the aquifer rather than direct use. There's also a very slow time of travel in this aquifer. We're talking about movement of less than a foot per day, and this in itself would give a final polishing to the effluent.

Q. *Shouldn't the quality of water used to recharge the aquifer system be comparable or compatible with the existing water quality in the aquifer? Will the State require tertiary treatment, such as nutrient and heavy metal removal from the water to be recharged?*
A. I think the quality of water will be comparable, at least within certain limits, to the water in the aquifer. The effluent will have to meet drinking water quality standards.

Q. *How do you remove nutrients (phosphates and nitrates) from your tertiary treatment plant?*
A. We have no plans at the present time for removing nitrates or phosphates. Nitrates were one of the chemical determinations made. The nitrate content was usually below 45 parts per million. Analysis for phosphates were not made.

Q. *Do you foresee any problems with the formation of algae due to the temperature of recharged water?*
A. We had problems with algae in the project and foresee problems during actual field injection.

Q. *Is it feasible to recharge storm water instead of treated sewage effluents? Are there any studies being undertaken on the kind of treatment required for storm water runoff to be used as recharge?*
A. Yes, it would be feasible. In relation to injecting into the deep sandstone aquifer, we would have to consider the storm water runoff as sewage effluent and treat it accordingly. We have made studies where the storm water runoff has been considered for use in pit or trench recharge in surficial formations.

Q. *If common law governs withdrawals of water, how will the recharged stored water be kept for the "recharger" instead of being withdrawn by another party?*
A. The "users" would have to be the "rechargers." In the Chicago region, in the deep sandstone aquifer with a well-defined piezometric surface, limiting flow lines could be drawn from the point of injection, or points of injection, to determine beneficiaries of the recharge water and charge the "user" based on the benefits from reduced pumping lifts. It is not proposed that the State of Illinois be the "recharger." We would operate a demonstration project and eventually a group of industries and/or municipalities would undertake the operation of the recharge installations.

Q. *Have you yet experienced the formation of organic clogging mass at the liquid-solid interface, as related to aquifer injection now, similar to the masses that are characteristic in a surface spreading operation for the field seepage of sewage effluents? The loss of infiltration capacity begins to show up in about 50-100 days as a result of these layers. How long have you run your system continuously?*
A. No, we didn't experience the build-up of these organic clogging mats. I don't believe we actually ran the experiments long enough. In answer to the question as to how long we ran the tests, this is what we hope to do in subsequent studies—be able to recharge for a longer period of time. The longest that we ran continuously was five days.

Q. *If the chloride ion is not removed from the sewage water, will a long-term recharge program ultimately result in brackish formation water?*
A. Well, I think you're talking about a period of time here. What I should point out is that since the aquifer will be depleted at some time in the future you will have a storage reservoir underneath the metropolitan area which can be used to great advantage. Its use, by not going into some sort of recharge program is greatly limited. We have only considered the recharging of sewage effluent in this particular study. There is also a possibility of recharging Lake Michigan water directly during periods when the levels in the lake are critically high.

Bull Session 1—Ground-Water Waste Disposal Recharge and Reuse

Session Chairman: James C. Warman, Director, Water Resources Research Institute, Auburn University, Auburn, Alabama 36830.

Leonardo Alvarez, Association of Engineering Geologists, Palo Alto, California:

I'd like to bring up a year-old question as to the direction of research that we should undertake in developing some criteria for disposal of wastes to wells. We notice that some of the projects we have in Illinois haven't run into any trouble and they don't expect to, but there are some ambiguities here and there which bring up the question, "Why is it so-and-so?" There is no answer. Why is the pressure head so-and-so, and there is not a logical answer. I'm bringing up this question—this topic—what do you think is the logical way to go about setting up some sort of criteria? I'm sure industry has done this for a long time, but does their work apply to what we are doing and, if it does, should we modify it, and so on and so forth.

James C. Warman, Lead Bull:

I'm sure you don't mean to say there is no answer—you mean to say we don't yet understand the answer.

John Rold, Colorado State Geol. Survey, Denver:

I think that most of the answers we are looking for about disposal wells are in the petroleum engineers' heads and in the research reports that petroleum engineers have read. When we started working in Colorado on our rules and regulations, we found that the petroleum engineers with major oil companies and research organizations had a fantastic amount of answers to questions that we, as geologists, hadn't even begun to comprehend when we started squirting something underground. We think of this as a new field. In Illinois, they talked about having four waste disposal sites and yet there are 13,000 underground brine disposal sites in the State. You have difference in viscosity of fluids and difference in compatibility, but they have been fighting this problem for 100 years. It may be that there is research yet to be done on compatibility of fluids and the like, and the behavior of fluids in the ground. This research would take a lot of monitoring—I feel that we need more monitoring than we are getting. Many of these wells, of course, are 7,000 feet deep and we're talking about a $40,000 or $50,000 hole just for monitoring. Then you have the possibility that your monitoring hole may be a leak in the injection aquifer. For most people concerned about injection wells, just going through the literature of the petroleum engineering profession, or getting with a good petroleum engineer, somebody like Hank Van Fulin, will give them most of the answers that we have.

Jack Talbot, Brazos Oil & Gas, Houston, Texas:

The preceding comment is very much in order and, certainly, Dr. Van Fulin and people of his stature, have contributed a great deal to the basic and fundamental information that has to do with this subject. But there are still differences. For example, some of the injected fluids are corrosive and difficult to clarify—much more so than oil field salt waters. Peculiar, subtle metallurgical and materials-engineering problems are involved, and some additional and new investigations really need to be made. One of the things that has surprised me and my colleagues is that there is so little information as regards the tolerance of permeable formations to suspended solids. We know we can pump things like cottonseed hulls into fractured limestones, and yet formations exhibiting intergranular porosity are very sensitive to suspended matter. But the degree of clarification required is not known. The question came up yesterday—can you inject 10-micron particles or is it only 0.3-micron particles? There is a great deal of work still to be done in this area.

John Fryberger, Consulting Ground-Water Geologist, Engineering Enterprises, Norman, Oklahoma:

The prime area where we have worked in Oklahoma is in salt water disposal wells, rather than industrial wastes. Our experience has shown that the oil companies are not applying the expertise that I'm sure they have, at least in salt water disposal. I can cite, as an example, salt water disposal wells in the Glorieta Formation where they had perforated 10 feet of casing in formation consisting of about 100 feet of fine-grain sandstone. Consequently they were using pressures up to about 500 psi ground surface for their salt water disposal in a formation capable of taking the salt water with no surface pressure applied. It's a matter of well design that made them use the pressure. I think we need a uniform requirement that a disposal well application should include, in the test drilling procedure, a determination of the transmissivity of the injection zone to be used. Once you know the transmissivity and use the projected injection rates, you can calculate the formation pressure build-up which may be far different from the required injection pressures because of skin losses and plugging of the injection well. If required, injection pressures might exceed what you would normally allow for formation pressure, but would still be a safe formation pressure to use. If you know the formation transmissivity, you can calculate what the formation pressure will be with time. This is a safeguard that I have not seen in my study of State regulations required now for injection wells. I'd like to see this adopted.

Speaker not identified:

Would these regulations be within the oil and gas industry? Or, within some other agency?

John Fryberger:

I would think that the regulatory agency charged with the responsibility of industrial waste wells should have this requirement. The regulatory agency responsible for salt water disposal wells, quite often is a separate agency.

Speaker not identified:

Do you think that there should be a dual responsibility?

John Fryberger:

No, but quite often, that's the way it is with the State agencies.

John Reid:

On the subject of regulations, Jay Lehr asked me to talk about Colorado's problems. We're the most recent State to come up with rules and regulations for disposal wells. I didn't get around to putting together a paper for the formal program, so he asked me to discuss this tonight. Colorado had the unhappy experience of having a deep waste disposal well which became quite famous, the Rocky Mountain Arsenal Well, without any rules and regulations. Then the State passed a law on water pollution and the Water Pollution Control Commission went through about a year of hearings on an application for a radioactive waste disposal well in northeast Colorado. They still didn't have any rules and regulations or guidelines. The applicant didn't know what was expected of him and the Water Pollution Control Commission didn't know what was expected of them, so they turned down the application after about a year's hearings.

The Commission then put together a Committee to come up with a set of rules and regulations. There were about 25 people on the Committee – geologists, lawyers, sanitary engineers, petroleum engineers, people from Dowell and Halburton Service Companies and many of our State agencies. We had a Geological Committee, a Reservoir Committee, a Sanitation or Health Committee and a Legal Committee. Everybody sat down and first of all wrote to all the States that had any experience with waste disposal wells and any laws—they picked all their brains. Then we made a basic policy decision before we started—that we couldn't go with hard and fast rules such as Illinois has used about 5,000 ppm and 10,000 ppm. One of the reasons is that some of our wastes in Colorado actually are good enough that they wouldn't hurt water of 2,000 ppm. We've been in the situation of having to inject oil field fluids that are 1000 ppm down a hole rather than let them run into a river of 1500 ppm.

We came up with a series of factors which should be considered individually for the situation at hand. There are 25 or 30 factors that have to be looked at—for example, the transmissivity of the reservoir and coefficient of storage. We realise that it may cost the company wanting a disposal well probably several hundred thousand dollars to get all of the data together that would be needed for an application. So, we have a preliminary application situation whereby the applicant can get together all the data he has, or can put together at a reasonable cost, and bring the proposition into the Water Pollution Control Commission and see if it has any chance of flying at all. So he has some idea as to whether or not they're going to let him go ahead with the proposal.

The application has to include a legal description and a map of the area with a two-mile radius of the proposed well, showing all the surface and mineral owners. It has to show all test holes and penetrations, description and depth of all the formations penetrated by any well or mine on the map, local topography, industry, fish and wild life, description of the mineral resources believed to be present in the area, and the probable effect of the system on the mineral resources. They have to have a geologic structure map showing stratigraphic sections, plus a geologic cross section drawn through the area and the proposed well, a description of all water resources, surface and subsurface, within the zone of influence or possible influence of the system, a classification of those waters, and a map showing vertical and lateral limits of surface and subsurface supplies. There must be a description of the chemical, physical, radiological and biological properties and characteristics of waste to be disposed of in the system, and treatment proposed for such waste including copies of all plans and specifications of the system and its appurtenances. A statement of all sources relied upon for information must be set forth in the application. If the system is to be an injection well, he has to have potentiometric surface maps of the disposal formations and those formations immediately above and below. Copies of all drill stem tests, installations and data used in making the maps must be included. We ran into that on a previous application because there were a lot of numbers on the map that couldn't be traced to basic data when we were trying to check them. You must state the location and nature of present and potential use of fluids from the disposal or affected formation and the volume, rate and injection pressure of the fluid to be injected. Then include the following geological and physical characteristics of the injection interval and the overlying and underlying permeable barrier: thickness, areal extent, lithology, that's grade, mineralogy, type mineralogy, matrix, amount and type of cement, clay content and clay mineralogy. You must include the effective porosity and how determined, permeability—vertical and horizontal—and how determined, mechanical logs, and formation tests. And you must furnish the coefficient of storage of the aquifer, the amount and extent of natural fracturing, location, extent and effects of known or suspected faulting, extent and effects of natural solution channels, the fluid saturation in the formation, the formation fluid chemistry with indicated local and regional variation, temperature of the formation and how determined, formation and fluid pressures, fracturing ingredients, osmotic characteristics of the rocks and fluids comprising and contiguous to the reservoir and an indication of the effect of the injected wastes on the contiguous formation in the event of leakage, diffusion and dispersion characteristics of wastes in the formation fluid and the effect of gravity segregation, the compatibility of injected wastes with physical, chemical and biological characteristics of the reservoir. And, of course, you must have the engineering data on the well which is normal and as detailed for the geology.

Now, you can see why we give them a chance for a preliminary go to see if their project applies. We didn't want any disposal wells unless we knew they were safe. Since these regulations went into effect on July 1, 1971, we have had an application and it was granted for a waste disposal well by Shell Oil Company, over in the Peonce Basin for an oil shale experiment. The regulations are feasible. Shell said it was a real pain in the neck and a lot of a problem but, by the time they made out their application, I think they knew more about the formation and their project than they did when they started.

Jack Talbot:

Do the oil field salt water disposers have to comply with these same requirements?

John Rold:

No. In Colorado the disposal of oil field brine is handled by the Oil and Gas Commission. They don't have to use these regulations; however, the Water Pollution Control Commission has essentially said, "Yes, the Oil and Gas Commission has authority over that, but if they goof up once, we'll take it over." So, it's putting a little bit more surveillance on the brine disposal.

Unidentified Speaker:

It is fortunate for the prospective injectors that Colorado is not a large industrial State, because the information that's requested here, if it *must* be supplied, is simply not available.

John Rold:

We are aware of that and aware of the probability that to get some of this data you'd actually have to drill one or more test holes down through the disposal aquifer. We weren't looking to become a haven for subsurface waste disposal wells. A lot of people said we'd never get one, but we've already got one after the regulations came into effect. Incidentally, the applicant for the unsuccessful operation that was turned down earlier and had so much trouble was on the Committee and helped write these rules.

Zane Spiegel, Ground-Water Hydrologist, Santa Fe, New Mexico:

I just wanted to ask if this well you speak of was in an area with existing knowledge from oil exploration.

John Rold:

There was an amount of existing regional information in that there were two or three holes that had been drilled within a few hundred feet, as well as the hole proposed for injection. So, they did have the required data.

James C. Warman:

Would anyone else like to comment on these regulations, their complexity or adequacy, or would you like to make other comments about regulations at the moment?

John Fryberger:

I'd like to ask a question of everyone here. Do you think it would be reasonable to require waste disposal well applicants to furnish the transmissivity . . . well, now, let me back up . . . in his application to furnish all of the background data that you were talking about—the existing wells in the area, the geological structure of the horizon that he would intend to inject into, information that he could obtain without actually drilling a hole down there, and have his application be either turned down on the basis of that information or tentatively accepted on the basis of that information. If it was tentatively accepted then he would be required to construct a well—if he wanted to do it this way—go right ahead and construct his disposal well as he would intend to use it, and perform tests to determine the transmissivity of the formation. Based on these tests, the regulatory agency could then determine that rate of injection at which the potentiometric surface in the injection zone would not be above the water table or potentiometric surface in the lowest fresh-water aquifer. And, at that rate of injection, even if there would be a leak, there'd be no way for the injected fluid to get into the fresh-water aquifer. So it would be, in a sense, a fail-safe type of operation. Do you follow me?

James C. Warman:

Are there any comments on that? That sounds like a practical approach to me.

Jack Talbot:

Well, it is a practical approach, and this is what almost all regulatory agencies do, regardless of whether the discharge is to a surface stream or to the subsurface, or whatever method is used. Any scheme that's used to control, or to alleviate a pollution problem is an interim thing. The permission to use it is an interim thing. I know of only one State that deviates from the policy—that requires a permit to drill a well for this purpose—and that's Alabama. Now you have to have there a permit to drill an exploratory oil or gas well. You have to have a permit to drill a salt water disposal well, but for some reason in Alabama you can go out with some understanding with the State people to make a penetration and get the data. Now they may, or may not, let you use the well, and this policy is the same as that followed by other States. This has the same policy as Louisiana. They can withdraw the permit at any time to discharge into the subsurface. As regards your limitations on pressure, there can be some real problems because of the nature of the fresh ground waters, the pressures under which they exist, and the pressures required to inject the effluent to the deep subsurface, these have to be examined on an individual basis and considered on an individual basis.

H. F. Smith, Illinois State Water Survey, Urbana, Illinois:

In Illinois, they have to have a permit to drill an exploratory hole for waste disposal. They need to furnish the information as best they know similar to what was outlined here in Colorado—maybe not so detailed. But then they get a permit to drill the exploratory hole and that is tested for its transmissivity and compatibility of the effluents and so forth. That was the case of the pilot hole that was drilled in a northern Illinois county. From all indications, the pilot hole looked like it would make a well. Following drilling, permeability tests, and running cores, they did try injection and couldn't get any injection—the well was abandoned. But, for all intents and purposes, it looked like a well until it got to that point. They had a permit to do it. One of the reasons I think they have a permit is because you have to specify the fluids you're going to inject. You can't deviate from that fluid without going back and having the permit corrected. The regulatory agency turns down a lot of applications because they just won't permit certain types of fluid to be injected. The permit to drill the well itself is a more or less temporary affair, but it's a permit. If they have demonstrated that it's a good well, then they do get a permit for operation. But, until that time, it's just a permit to test and the permit is required to even start off with one hole.

James C. Warman:

As John Fryberger pointed out, most of the regulatory agencies are approaching these requests for permits to construct a disposal well on the same basis that they consider a request to dispose of a liquid effluent to a surface stream. The request for a permit to dispose an effluent to a stream carries with it a description—some characterization—of the fluid, the quantities, and also the kind of treatment that you are giving this material before you are turning it loose, or proposing to turn it loose. These same kinds of things are considered by the regulatory agencies on this disposal proposition. You're not just going in to request to punch an exploratory hole, but you're really going in with a reasonably complete design package of the kind of hole you're going to drill, how you're going to construct it, the kind of tests that you're going to run on this well that will provide the data that will give assurance to the regulatory agency that you have considered these several parameters that we need be concerned with to satisfy ourselves that we're not going to violate the fresh-water aquifers. I don't know of any State that isn't really looking toward this approach. Some of them are doing it more or less thoroughly than others and I suspect most States that are getting into this will move toward tightening up these requirements for even this preliminary or feasibility approach, rather than making it easier as we go along. Now, if we have explored this facet to your satisfaction—if no one objects—I'd like to revert back to the original question, which was, "What kinds of research might we need to get into to provide some of the answers that we do not now have?"

Zane Spiegel:

I'd like to make one comment about Mr. Fryberger's question or suggestion in relation to the relative heads in the injection zone, or proposed injection zone, and the heads of overlying fresh-water aquifers. I think we have two general circumstances that we might encounter in this problem. One is a normal circumstance in which the deep aquifers, or salt water zones, already have a higher head than the overlying fresh zone. And this is actually the normal circumstance. In much of Oklahoma, Texas and southeastern New Mexico, oil and gas production has been going on since the 1920's or 1930's and early 1940's. The pressures in these lower zones—the salt water bearing zones—have been lowered to the extent that they are much lower than the overlying zones. Therefore, you could adhere to his proposal very easily, and inject significant quantities of water under substantial new heads—differential heads—without exceeding these fresh-water heads. But I think in virgin areas that have not had their potentials lowered by previous production of either oil or salt water, it might not be possible to do what you suggest.

James C. Warman:

What we're saying again is that each case is an individual case and must be considered only on that basis. Now, let me try again to revert back to the first question which got such short treatment. Where are the areas of knowledge in which we are quite lacking? Where are the research areas? Where do we need some help?

John Rold:

I'd like to throw one out that's really been bugging us, and that's the seismic effects of injection. We have one in our backyard, here, which has been blamed for several thousand earthquakes and the people that know more about seismic activity than I—some of the real experts in this area—don't believe it. Most people feel it probably is so probably because the proponents of the theory have gotten better coverage than the people that are against it. You've probably even seen in such journals as *True Magazine* about the seismic effects of the arsenal well. We, however, also have an injection—which is salt water this time, just an ordinary salt water injection pressure maintenance over in an oil field—and they are monitoring a lot of earthquakes in that oil field. They're all small, Richter magnitudes of 1, 2, and every two or three years you get one in that area that you can feel. But, of course, everybody's watching and waiting for them now. This possible seismic effect of injection wells is one avenue that really ought to be studied in considerable detail and very thoroughly, or we'll get slapped.

You may have heard that the GSA Meeting in Milwaukee had an excellent paper on the Seismic Effect of Dams, i.e., the loading of a dam with water causing seismic effects. The speaker had five charts and the statistical correlation was beautiful to show that they built the dam and then the earthquakes started. When he was about done he said, "Oh, by the way, that number four, they never built the dam." So, if you start monitoring any area with a good enough seismograph, you're going to pick up a lot of earthquakes. If I were an oil company, I'd be monitoring any area—especially an area of population—the day after I got the idea that I might start injecting fluid into a reservoir.

Frank Kresse, W. A. Wahler & Assoc., Palo Alto, California:

The U. S. Geological Survey is trying to trigger earthquakes with the idea of controlling major earthquakes. Of course, this is a very exotic thing, but they're really talking about this seriously. The idea is to construct an injection well along a fault that has a potential for major earthquakes and, by injecting fluids, cause small earthquakes that are undamaging to the point that the strain is taken off the fault. This is wrought with all kinds of problems as we can all imagine. That's really the kind of thing that they're imagining with this experiment and it should provoke quite a bit of discussion and thought, anyhow. I'd like to regress just a little bit. Most of you are familiar with the Baldwin Reservoir failure in the Los Angeles area in 1963. The failure of this dam was caused by a fault offset under the reservoir and under the dam, and the classic explanation for this was that it was caused by subsidence from oil withdrawal in adjacent oil fields. There was a $30 million lawsuit which was settled out of court. After the settlement some of the things that probably occurred came out and there's been a couple of papers—Doug Hamilton's and others on this particular thing. They've given a pretty good case for the idea that this offset was caused not by the subsidence, but by injection of water flooding of this same oil field, and that the offset was really a jacking effect of the fault itself which caused the failure. They've got a lot of time and space correlation and so on, and I feel that this surely was the thing that happened here.

So this is an example of what can happen, maybe an unusual one, but one of the other things that can happen from injection wells. I think there are at least three or four cases that have enough documentation where there can be little doubt that this has happened. When I was involved in the Baldwin Reservoir lawsuit, I went through the literature and tried to find all of the cases where there was at least some documentation and I feel that there are at least 12 cases, world-wide, where there is at least some evidence of increasing earthquake activity due to the construction of a reservoir.

Jack Talbot:

I wonder if an initial bit of research couldn't be simply to find out reasonably how many types of injection wells there are in the country, and where they are. No one seems to know this. How many wells inject salt water into formations other than that of origin? What have been the seismic effects of this? And what have been the effects of withdrawals, not as regards subsidence, but as regards earth tremors? I think someone could do a good study of the literature and the records that we have in this country and come up with some useful information. It may allay some of the apprehensions that go with injection of fluids and building dams and the like.

James C. Warman:

One of the things in which we can stand a little research is in the pure economics of what it really is going to cost to go through the kinds of testing that the regulatory agencies are going to have to require—the construction and the testing of the well itself, and the operation and monitoring of this well. Then we get into the philosophical bit about who's going to pay for the monitoring. I'm not sure where that cost needs to fall. We've had some research going on in Alabama by Dr. David M. Grubbs at the University of Alabama. Dr. Grubbs has been working with well logs from Oil and Gas Board records and other existing information. He sought to determine the most probable areas, especially in the Coastal Plain part of Alabama, where you might likely be successful in deep well disposal. He used available data to put together ideas on how much liquid of what kind you could inject in these zones in these various feasible sites that he has identified. And then he's tied this thing into your need as an industry with a given effluent. If you will characterize the effluent, the quantity and type of material you want to get rid of, he will take your disposal requirements, consider the geographic, hydrologic, and geologic setting in which you want to operate, and run all this through the computer. The computer will—on the machine—drill a well and attempt to operate that well to meet your requirements. If it can't accept your waste in the quantities that you want to get rid of and the pressures that you're going to have to handle, the computer will drill another well and carry cost data with this.

This approach needs refinement, but it's interesting and promising. If the computer indicates that you have to drill five wells, you look at the economics of this and say, "Yes, I can handle that kind of expense in the construction and operation costs to dispose of my waste that way." Or you may say, "No, this is out of the ball park and we have to find a better way to treat this waste at the surface and get rid of it with conventional or new technology."

Other kinds of work going on at the University of Alabama and elsewhere are concerned with compatibility of some of the wastes that we know people are going to try to dispose of through deep wells—the compatibility of this waste with the liquid in the reservoir and with the reservoir rock itself. What other kinds of problems are we going to have to solve before we can move on with safety?

Richard J. Schicht, Illinois State Water Survey, Urbana, Illinois:

Has anyone here had any experience using a buffer fluid injected before the waste effluent?

Jack Talbot:

Yes, I've been involved in this and it is one of the less exact sciences. Sometimes I think the reason this is done is to make everyone feel better. I'm not really sure what purpose injection of the buffer fluid, usually fresh water, serves. But it is convenient, besides making everyone feel better, in that when you start injecting fluid into a well it's prudent, normally, to test the surface equipment and it's nice to do this with fresh water, so you pump a calculated volume. We use a formula that Don Warner developed—or his colleagues did—at the Taft Sanitary Engineering Center, which, so far, has worked like a charm. But I'm not really sure that the buffer fluids are necessary. I'd like to say something about compatibility. A great deal of research can be done in this area, but I'm not sure that this is one of the problems of injecting strange fluids into a formation. We've had the experience of taking a core—a limestone core—of intergranular porosity and injecting dilute sulfuric acid into it and plugging it immediately. Yet, in a real life situation in the field, it works fine. Now these are very dilute acid sulfates, and I can't suggest what the result would be if you injected a more concentrated solution. The compatibility is something that one should be concerned about; but the fact that core lab work says that you're going to plug the formation need not stop you from making an attempt.

James C. Warman:

Any more than when core lab work says it won't plug the formation is this a guarantee that injection will be a success. Laboratory results do offer some mighty good cautions. If you were considering an effluent that immediately plugged a porous limestone core that came from your host rock, you'd at least better have your eyes open.

Jack Talbot:

Exactly. I'm not denying that caution should be used in this area. I'm just saying that if a person or a company has a difficult injection problem and there appears to be no other way to solve it, he should not drill the well based solely upon the laboratory data. Incidentally, the tendency around the country is becoming more and more to insist that the applicant examine all reasonable alternative means—sometimes unreasonable alternatives—to the solution of his pollution problem. This is something I, personally, agree with. The subsurface is limited in its volume, its capacity, and its ability to accept these fluids, and things that can be treated on the surface really ought to be treated there. But, at the same time, there are streams generated by manufacturing plants that have so far defied human ingenuity in solving the surface treatment. And there are those who say there will never be a solution; they may be overly pessimistic. The chemists tell me that the chloride effluent is one very tough problem.

Zane Spiegel:

I have comments on three points and I'll go backwards. One is that I agree completely with that last statement about the alternatives, because one of the alternatives I think that is being proposed more and more is a recycling type of treatment in which things are recovered. Many cases have been mentioned in the last two days where an industry has been forced to do something like that and afterwards they've discovered that recovery was really the most profitable thing to do in the first place. I guess we haven't looked at these things carefully enough and the future of recycling is going to become more and more attractive. The second point is that I think an obvious explanation for the difference between laboratory results and occasional better results from actual tests on formations is that there may be denser porosity in the core because the core obviously is a piece that hasn't been fractured. The third point is to go back to the kind of basic research that is needed. I don't know whether you'd want to call it research or not. It's just a collection of the kind of basic data that we need, the actual formation potentials that exist and sometimes can be obtained from existing files of data, particularly in the oil industry, and development of better methods of collecting these data. I think the oil industry has been working on that for the last few years. They were rather lax in doing that in the earlier years. Much of the data that we do have is either of no value now because conditions have changed or it was never of any value because the data was just no good to start with. One of the basic things we need is development and application of methods of collecting good data on existing wells.

John Fryberger:

I'd like to expand on what Mr. Spiegel was just saying. You're referring to the problem of gathering information on existing wells in the area where the proposed injection well is to be drilled, and especially those wells for which there is no record. That's a tough one. In some work that I've done recently, I've tried to gather data on problems that have been created due to salt water disposal or water flood operations in contamination of ground water or surface water supply.

One example that really sticks in my mind is where they had an injection well about 3,000 feet deep for water flood and about a quarter of a mile away there was a hole about 500 feet deep. I don't even know why the hole was drilled. Some time after injection was started, salt water poured from this 500 feet deep hole and it obviously was coming from this 3,000 feet deep injection well. It flowed out at the rate of several hundred barrels a day, flowed into a stream and contaminated the stream for 15 or 20 miles before it was finally observed. That illustrates how water might move underground from one zone up to other zones, maybe through several wells, interconnecting different zones.

This, to me, illustrates the futility in a way of having observation wells—monitoring wells—in the vicinity of an injection well. I really don't think the information that these safeguards obtain would be worth the expense, because water can move a considerable distance away from the injection well before it comes up through a fracture zone and never be detected in any monitoring system. So, I haven't been able to envision in my own mind a monitoring system that would really do the job at a reasonable cost.

Jack Talbot:

If you're talking about intergranular porosity rocks, I just can't agree with that because in an injection system situation your greatest pressure difference between the natural head and the injection formation and the injection pressure exists at the well bore. For what you're talking about, something could happen where fractured porosity exists. But we worry more about the well itself in an intergranular porosity situation, which is what we like to stay with, than we do about what is going to happen out away from the well bore a half mile or so, or even less, because at that distance where the porosity is intergranular and possesses some reasonable degree of homogeneity, the difference between your natural pressure and your injection profile is going to be minimal. In the case you described, I would suspect that you've just recited a bad cement job.

John Fryberger:

This was in SE Kansas where the water was coming up the 500 feet deep well from a 3,000 feet deep injection well—I didn't get much more information other than the specific depth. I got the information from the Kansas Health Department.

You would propose then putting monitoring wells, say within ten feet—or some very close proximity to the injection well—is that right?

Jack Talbot:

I probably wouldn't want to inject in an area like southeastern Kansas in the first place. If you're talking about somewhere else where the rocks possess reasonable permeability and porosity and the geology is fairly well known—yes, I would want the monitor well near the injection well. Or, perhaps the injection well itself could be engineered to serve as a monitor well.

John Fryberger:

Yes, I like that idea, but if you had a separate monitoring well you would probably want to put it to the bottom of the lowest fresh water zone. However, it might be likely that there would be other permeable zones below the lowest fresh water that could take the injection fluid that might be coming up alongside the casing because of a poor cement job, and the fluid would move laterally and might find some other avenue up. There are so many geologic conditions that, in my opinion, make monitoring not too feasible. In some cases it would be. As a general thing, I don't think I'd be for it.

John Roid:

One of the things I think we're going to be faced with in the near future is the highly toxic fluids—the real problem fluids. As soon as the Corps of Engineers puts the clamps down on waste going into navigable streams or their tributaries we are going to have a lot of people thinking, "Well, maybe we ought to put it down a hole." Many of these fluids are not too bad. There's no real problem with some of the fluids and it could be fairly economical, in many instances, to put in an injection well and get rid of these rather innocuous or fairly safe fluids that way. Of course, once you say underground waste disposal well in most circles, you've got a fantastic emotional problem. Everybody, including the Sierra Club, is very down on underground waste disposal wells.

But I think that we should start thinking in terms of our being a lot better off to put a lot of these fluids in a salt water formation at 3,000 feet than running them down the river. There's an awful lot of that going on. We're just now beginning to find out how much liquid is being surreptitiously or otherwise run into a storm sewer or a sanitary sewer or into a creek. I think that we're going to be facing a lot of small-time innocuous fluids that could well be put underground. There again, each case should be looked at on its own merit.

Jack Woodard, Florida Dept. of Natural Resources, Tallahassee, Florida:

We've already hit the spots you were just referring to about getting some of the rather innocuous materials out of surface streams, especially in the southeastern section of Florida. In Florida half of our deep injection wells are disposing of treated sewage effluent. We're afraid we might want to salvage some of this stuff at a later date. Also, we don't have much room to build dams for storage reservoirs in south Florida. We're looking at disposal wells seriously with the idea of injecting storm water and recovering it at a later date. There is a little bit in the literature about this, but I would like to hear, particularly, from any of the State regulatory agencies who have criteria on what it would take to inject with the idea of recovering this particular water. And I might add that we are putting storm water into a salt water formation. Everything from 200 feet down to a 3000 feet injection horizon is a poorer quality than what we're putting into the 3000 horizon so I am not too worried about leakage.

Richard J. Schicht:

I don't know if you're familiar with the USGS project in Norfolk, Virginia. I think they're doing something similar.

Jack Talbot:

I'd like to ask Mr. Woodard if there are any plans to do some experimentation for testing to determine or estimate what the quality of fresh water will be if it's injected into a saline aquifer and then recovered. It seems to me that this is something that needs to be known before there's a great deal of money and effort spent in this sort of thing.

Jack Woodard:

Israel didn't have very good luck with their project and recovery rates. It has proven to be economically feasible to dispose of storm water and particularly sewage effluents into deep storage wells, but both of these procedures are fairly new. Right now the entire amount of the monitoring program in Florida is handled by the private industry which injects the waste. I'm trying to get some program set up for research in this area, but I was looking particularly for anybody who might be doing that. I'm going to pick their brain.

Zane Spiegel:

I know of a couple of cases where water was injected into sandstone aquifers and then recovered at a fairly reasonable rate of recovery—something near 80% as I recall.

Jack Woodard:

Yes. Everything I have found has been in the sandstone aquifers and we don't have any.

James C. Warman:

All right. Anybody want to shift gears?

John Farbiter :

I would like to ask a question of people who might know. What fluid is normally used in the annulus between the long string and the injection tubing? The ideal fluid would be noncorrosive and nonelectrolyte. I've heard that diesel oil can be used.

Richard J. Schicht :

That is what they are using in Illinois. I haven't heard any complaints about it up to now so it seems to be working all right.

John Farbiter:

That's the only one that I've heard of and I was just wondering if there have been others.

Unidentified:

Most commonly, fresh water is used. In my experience you can add an oxygen scavenger if you want to be especially particular about it, but normally this isn't done. Mud is normally avoided because of the problems of fishing the injection tube out after some period of operation.

Dick Brown, U. S. Geol. Survey, Lubbock, Texas:

I was waiting to hear someone start on injection of surface water into aquifers, especially aquifers as a recharge operation. We're involved in the research in the high plains on artificial recharge. I thought that when this time came I would comment on your question as to what size particles you could get into an aquifer system. We don't really know this, of course, but we have done a little work which we thought was interesting.

We have sand columns in the laboratory and these consist of fine and medium sand. We have injected through these columns at a range of from 20 to 50 psi at a constant rate. We get a reduction in permeability of 70% on some of these. We've taken cores out of these columns and sent them to Sperry Rand and had scanning electron micrographs made of the materials taken from the columns after they are plugged to this extent. What has surprised us greatly is that in the scanning micrographs, sediments look as if they're an open boulder field, and the surface deposit is kind of a layer of seaweed over the sand grains and you don't even see it until you get to 10,000 magnification, and yet this is enough to cut permeability 70%. We have not done much with different kinds of clays yet. In preliminary experiments we ran a mixture of kaolinite and water through millipor filters; then we ran pure water and then a mixture of montmorillonite and water and we found that we got a couple of orders of magnitude more water through in a given amount of time with the kaolinite than we did with the montmorillonite. In fact we got more water through with kaolinite than water by itself. This was 500 mg. per liter of kaolinite, and then we ran 500 mg. per liter of kaolinite through first and ran the montmorillonite through later and got more montmorillonite through than we had through the filter without any kaolinite on it.

So it makes a big difference as to what you run through. In much of the literature on artificial recharge you see the sediment content expressed as a Jackson Turbidity Unit and here again the JTU readings for a kaolinite-water mixture are totally different than for a montmorillonite-water mixture. There is a magnitude of difference in JTU units for the same concentrations, so there is a great deal of work to be done.

James C. Warman:

Having solved "all" the problems of deep well disposal, I think we may have run down for this evening. Thank you all for coming in and participating in the bull session. I think it's been a lot of fun to sit down together and go at it this way. We learned a lot by listening to the formal speakers and having a chance to write questions to them, but this bull session is another kind of dialogue that is also quite helpful. We probably need to do more of this, and less of that, with all deference. More auspicious groups, for example the Gordon Research Conferences, have found that this type of dialogue can be highly productive. We hope that this bull session and the other three underway this evening will have turned out some thoughts that we can all pick up from the Proceedings of this Symposium. Let's get on with the business of solving problems. Thank you.

Pesticide Contamination of a Shallow Bored Well in the Southeastern Coastal Plains[a]

by M. J. Lewallen[b]

ABSTRACT

A comprehensive examination was made of a shallow farm well which was contaminated with persistent pesticides when contaminated soil was used as backfill material around the well casing. The well location was less than 25 feet from a site previously used for flushing an insecticide sprayer.

Pesticide level in the water has been monitored for more than 4 years, during which a gradual decline in concentration has occurred. Soil core samples taken in the area surrounding the well indicate relatively high surface contamination but very little downward movement. Sediment samples from the bottom of the well exhibited highest concentration of all samples.

INTRODUCTION

Pesticide contamination of water supplies is a matter of concern to all people associated with water quality. Because of this interest, many investigations have been conducted concerning the occurrence, cause, and solution of problems associated with pesticide contamination. However, most research has been directed toward surface water and municipal supplies.

Large amounts of pesticides are handled and possibly even stored in close proximity to many individual water supplies. Quite often these materials are in their most concentrated form when they are closest to the water supply. Such situations can occur during filling and flushing of sprayers. Regardless of these seemingly great hazards, few documented cases exist of pesticide contamination of individual water supplies. This report documents the occurrence and describes the conditions which allowed toxaphene, DDT [1, 1, 1-trichloro-2, 2-bis-(*p*-chlorophenyl) ethane] and its metabolites to enter a private water supply in the southeastern Coastal Plains.

Well Construction

The well was constructed in late 1966 and is typical of many installations in the Southeast, where rather small water yields are required and geologic formations permit the boring of a large diameter hole. Typically, the well is 30 inches in diameter and cased with 24 inches inside-diameter concrete pipes which are 48 inches long. The pipes are fitted together by a tongue-and-groove type joint without sealing joints in the casing. Depth of the well is 40 feet, and the water table averages approximately 18 feet below the surface.

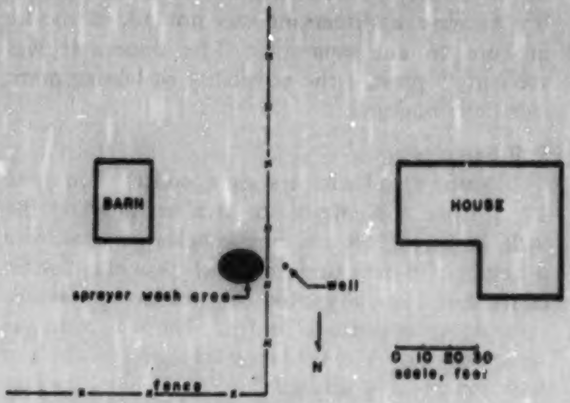

Fig. 1. Layout of the farm yard.

Contrary to established recommendations (U. S. Department of Health, Education, and Welfare, 1962), soil was backfilled around the well casing without using either concrete or clay grout. Typically, after a few days the inadequately compacted backfill settled, producing a maze of channels through the backfill material. The owner then removed soil from an adjoining area which had been used to fill and flush the farm sprayer and placed the contaminated soil around the well casing. Layout of the farm yard is shown in Figure 1. Within a few days pesticide contamination was detectable organoleptically in the water.

EXPERIMENTAL PROCEDURE

Water Samples

Collection of water samples began in January 1967 and has continued periodically since that time. Typically, 4-liter samples were collected at the tap adjacent to the pump. Samples were returned immediately to the laboratory and extracted in accordance with FWPCA methods (U. S. Department of the Interior, 1969).

Sediment Samples

Sediment samples have been taken from the well bottom both to reduce contamination as well as for analysis. The first sample was obtained by bucket in August 1968. Additional sediment was pumped from the well in September 1969 and again in February 1970. Fractionation by gravity separation was attempted on the latter sample to obtain estimates of the pesticide load carried by each particle size range. However, complete separation of the silt-clay particles was not obtainable probably because a dispersant was not added to the mixture to aid separation. The dispersant was avoided to prevent the possibility of biasing pesticide determination.

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[a] Contribution from the Livestock Engineering and Farm Structures Branch, Agricultural Engineering Research Division, Agricultural Research Service, USDA. Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

[b] Agricultural Engineer, U. S. Department of Agriculture, Southern Piedmont Conservation Research Center, Watkinsville, Georgia 30677.

Soil Samples

Surface soil samples were collected in June 1968 from the immediate area surrounding the well. In July 1968, soil core samples were taken to a depth of 6 feet using a 3-inch diameter bucket auger. Soil backfill around the well casing was also sampled to a depth of 4 feet. The soil core was separated into 1-foot increments except the top foot which was divided into a 0-3-inch surface sample and a 3-12-inch subsurface sample. Core samples were taken again in June 1969 in the area of highest contamination. The sampling device used was an impact driven sampling tube. These soil cores were separated into 1-foot increments except the top foot which was divided into three 4-inch samples. Soil samples were air dried in the laboratory and extracted using the method of Guenzi and Beard (1967).

All samples were analyzed for the presence of toxaphene, DDT, DDD [1, 1-dichloro-2, 2-bis-(*p*-chlorophenyl) ethane], and DDE [1, 1-dichloro-2, 2-bis-(*p*-chlorophenyl) ethylene] using electron capture equipped gas-liquid chromatographs. Quantification methods used in this study are described in *FDA Pesticide Analytical Manual* (U. S. Department of Health, Education, and Welfare, 1968).

RESULTS AND DISCUSSION

Water Samples

Analysis of water samples taken in January 1967 showed 20.1, 1.5 and 0.5 ppb (μg/liter) of toxaphene, DDT, and DDE, respectively, while March levels declined to 9.3, 0.5 and 0.3 ppb, respectively. Contaminant levels continued to decline, and in June 1968 levels were 8.4, 0.1 and 0.1 ppb of toxaphene, DDT, and DDE, respectively. The June 1968 sample was the last one to exhibit contamination levels greater than the criteria established for public water supplies (U. S. Department of the Interior, 1968). Figures 2, 3, and 4 show that contaminant levels have oscillated at relatively low levels from summer 1967 until the present. Presumably an equilibrium exists in the pesticide content of the sediment and water. This is controlled by the absorptive capacity of the sediment and the solubility of the pesticides in water. Solubility of DDT is reported to be 1.2 ppb at 25 degrees C (Bowman, Acree, and Corbett, 1960).

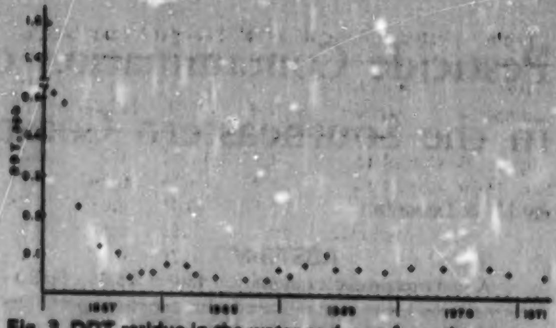

Fig. 2. DDT residue in the water as drawn from the tap.

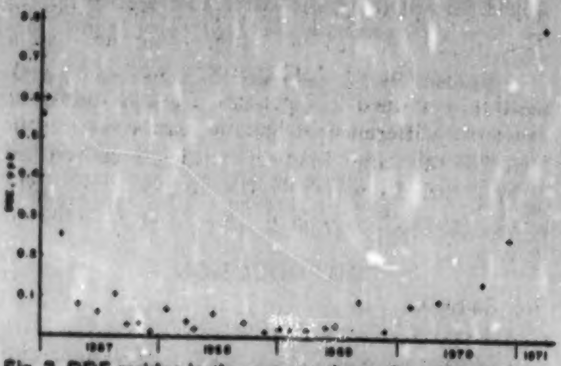

Fig. 3. DDE residue in the water as drawn from the tap.

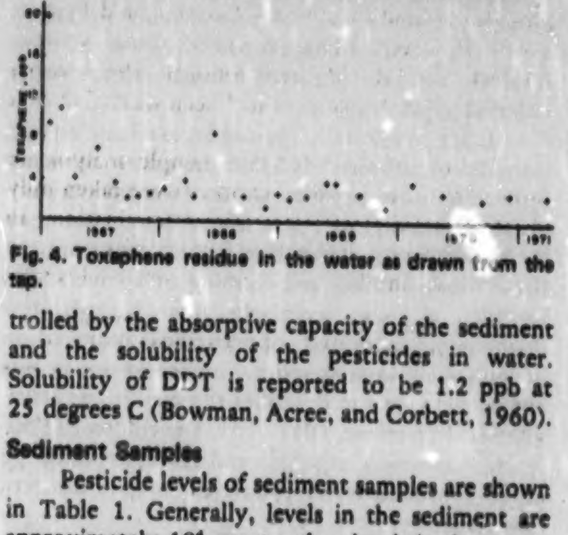

Fig. 4. Toxaphene residue in the water as drawn from the tap.

Sediment Samples

Pesticide levels of sediment samples are shown in Table 1. Generally, levels in the sediment are approximately 10^4 greater than levels in the water. An exception to this is DDD which appears in sediment and does not appear in the water. Physical characteristics of the sediment such as color and particle size appear identical to that of surface soil. Hence, both appearance and results of pesticide analysis indicate that contaminated surface soil has been transferred to the well bottom.

Incomplete fractionation of the February 1970 sediment samples prevent the drawing of definite conclusions regarding the relative pesticide load of each particle size range. Reasons are not completely clear as to why the combined silt-clay

Table 1. Pesticide Residue in Well Sediment, ppm (ug/g)

Time of sample	*Complete or fraction*	*DDT*	*DDD*	*DDE*	*Toxaphene*
Aug. 1968	Complete	8.75	11.61	1.25	34.6
Sept. 1969	Complete	3.93	8.65	0.24	6.85
Feb. 1970	Sand	0.13	0.35	0.05	0.88
	Silt and clay	10.1	7.51	0.66	10.2
	Clay	0.48	2.30	0.17	2.55
	Organic matter	23.8	145.0	13.3	235.0

mixture contained more pesticide than did the clay fraction. A significant contributing factor to these results is that the silt-clay mixture had a carbon content of 1.41 percent while the clay fraction contained 1.23 percent. The importance of this small difference in organic matter is accentuated by the large load of pesticide carried by organic matters which was sieved from the sediment. Result of analysis of organic matter is shown in Table 1.

Soil Samples

Results of the residue analysis of surface samples are given in Table 2. These values generally agree with those reported in a survey made of agricultural land (Trautman, Chesters, and Pionke, 1968). However, increased levels in an area about 15 feet east of the well confirms the owner's statement that his sprayer had been washed at that location.

Table 2. Pesticide Residue in Surface 3 Inches of Soil Surrounding Well, June 1968, ppm (µg/g)

Distance in feet and direction from well	*DDT*	*DDD*	*DDE*	*Toxaphene*
Backfill–N	0.120	.060	.045	0.300
Backfill–E	.123	.089	.051	.330
Backfill–S	.179	.043	.027	.270
Backfill–W	.086	.074	.011	.136
5–N	.322	.163	.074	.400
10–N	.154	.036	.048	.450
5–E	.486	.185	.063	.666
10–E	.176	–	.059	.583
15–E	6.66	–	.661	20.81
20–E	0.529	–	.146	1.64
25–E	.471	–	.139	1.45
30–E	.203	–	.073	0.636
5–S	.310	.052	.035	.346
10–S	.062	.046	.024	.231
15–S	.900	.507	.134	1.33
5–W	.046	.044	.009	0.182
10–W	.155	.102	.041	.270
15–W	.191	.130	.036	.320

Table 3. Pesticide Residue in Soil Core Samples, July 1968, ppm (µg/g)

Distance in feet and direction from well	*Sample depth*	*DDT*	*DDD*	*DDE*	*Toxaphene*
Backfill	Surface 3 inches	.131	.057	.047	.300
	1 foot	.125	–	.041	.154
	2 feet	.098	–	.045	.230
	3 feet	.116	–	.051	.108
	4 feet	.174	–	.068	.462
5–East	Surface 3 inches	.191	–	.054	.231
	1 foot	T*	T	T	–
	2 feet	–	–	–	–
	3 feet	T	–	T	.038
	4 feet	–	–	–	–
	5 feet	–	–	–	–
	6 feet	T	–	T	–
15–East	Surface 3 inches	5.125	–	.842	16.15
	1 foot	0.995	–	.205	3.385
	2 feet	.022	–	T	0.115
	3 feet	T	–	T	–
	4 feet	T	–	T	–
	5 feet	T	–	T	–
	6 feet	T	–	T	–
20–East	Surface 3 inches	.025	–	.012	.102
	1 foot	.171	–	.079	.500
	2 feet	–	–	T	T
	3 feet	–	–	T	T
	4 feet	–	–	T	–
	5 feet	–	–	T	–
	6 feet	–	–	T	T
25–East	Surface 3 inches	.156	–	.067	.385
	1 foot	.045	–	.016	.154
	2 feet	–	–	–	–
	3 feet	T	–	T	–
	4 feet	–	–	–	–
	5 feet	T	–	T	–
	6 feet	.011	T	T	.077

* Values less than .010 ppm are shown as trace (T).

Results of the 1968 core sample analysis are shown in Table 3. These samples were taken only in the direction of greatest contamination. In general, values for the top 3-inch samples agree with those in Table 3. Results of analysis of successive depth samples show that essentially all contaminants are contained in the top 12 inches of soil. Some measurable amount appeared in deeper samples, but sampling techniques allowed the possibility of cross contamination due to repeated insertions of the bucket auger into the bore hole.

Core sampling techniques that were used in 1969 prevented cross contamination and provided less erratic values among the deeper samples. These results are shown in Table 4. In only one sampling site, 5 feet east, did contaminants appear to have moved more than 12 inches downward. A possible reason for this exception is that this site could have been adjacent to the earlier sample hole where surface soil had partially refilled the hole, thereby carrying contamination downward.

Results of samples from backfill around the well casing show significant and relatively constant contamination to a depth of 8 feet. Contaminant levels in the well sediment lead to the assumption that contamination exists in the soil backfill for the complete depth of the well.

Table 4. Pesticide Residue in Soil Core Samples, June 1969, ppm (μg/g)

Distance in feet and direction from well	*Sample depth*	*DDT*	*DDD*	*DDE*	*Toxaphene*
Backfill	0-4 inches	.019	–	.012	–
	4-8 inches	–	–	–	–
	8-12 inches	.013	–	T*	–
	1-2 feet	.080	–	.030	.208
	2-3 feet	.161	–	.017	.543
	3-4 feet	.187	–	.051	.543
	4-5 feet	1.516	–	.245	5.208
	5-6 feet	.733	–	.112	3.400
	6-7 feet	.654	–	.093	3.000
	7-8 feet	.573	–	.091	2.253
5–East	0-4 inches	.049	–	.015	–
	4-8 inches	.091	–	.032	.417
	8-12 inches	.024	–	T	–
	1-2 feet	.014	–	T	–
	2-3 feet	T	–	T	–
	3-4 feet	T	–	T	–
	4-5 feet	–	–	–	–
	5-6 feet	–	–	–	–
	6-7 feet	–	–	–	–
10–East	0-4 inches	.198	–	.055	.700
	4-8 inches	.024	–	.018	–
	8-12 inches	.012	–	.015	–
	1-2 feet	–	–	–	–
	2-3 feet	–	–	–	–
	3-4 feet	–	–	–	–
	4-5 feet	–	–	–	–
	5-6 feet	–	–	–	–
	6-7 feet	–	–	–	–
15–East	0-4 inches	1.196	–	.283	7.128
	4-8 inches	T	–	T	–
	8-12 inches	T	–	T	–
	1-2 feet	–	–	–	–
	2-3 feet	–	–	–	–
	3-4 feet	T	–	T	–
	4-5 feet	–	–	–	–
	5-6 feet	T	–	T	–
	6-7 feet	–	–	–	–
20–East	0-4 inches	.188	.045	.055	.625
	4-8 inches	.020	–	T	–
	8-12 inches	T	–	T	–
	1-2 feet	–	–	–	–
	2-3 feet	–	–	–	–
	3-4 feet	–	–	–	–
	4-5 feet	–	–	–	–
	5-6 feet	–	–	–	–
	6-7 feet	–	–	–	–
25–East	0-4 inches	.086	.025	.025	.217
	4-8 inches	–	–	T	–
	8-12 inches	–	–	T	–
	1-2 feet	–	–	–	–
	2-3 feet	–	–	–	–
	3-4 feet	–	–	–	–
	4-5 feet	–	–	–	–
	5-6 feet	–	–	–	–
	6-7 feet	–	–	–	–

* Values less than .010 ppm are shown as trace (T).

The occurrence of DDD in sediment samples and its absence in soil backfill samples, as well as water samples, raised questions beyond the scope of this study. However, Miskus, Blair, and Casida (1965) studied the conversion of DDT to DDD in lake water and concluded that oxygen content of the water helped control the conversion rate. Also, they concluded that DDD appears to be more stable than DDT under certain conditions.

SUMMARY

This study of a private water supply demonstrates the susceptibility of improperly constructed wells to contamination with pesticides. Results of monitoring water and soil samples for more than 4 years point to the persistence of both DDT and toxaphene. Probably because of very low solubilities of these insecticides in water, contamination in the water remained low. Contamination levels in the sediment were much higher. Soil sampling in the area around the well indicates the pesticides have moved only slightly downward, and contamination of the well occurred through the movement to the water table of surface soil containing adsorbed pesticides.

Results of these studies emphasize the importance of good design and proper installation for shallow wells on farms.

The author gratefully acknowledges the assistance of Dr. A. W. White, Soil Scientist, in the analytical determinations made in this study.

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DISCUSSION

The following questions were answered by M. J. Lewallen after delivering his talk entitled "Pesticide Contamination of a Shallow Bored Well in the Southeastern Coastal Plains."

Q. *Was this a routine sampling? Did the owner suspect contamination and request specific analysis? Did this result from a special survey or study or were there other reasons for sampling and analyses?*
A. Contamination was detected by taste in the water in this instance. I think, in general, most of these materials we're speaking of have taste thresholds in the low parts per billion range. In this particular instance, the owner detected a strange taste and odor in the water. At that point he realized what had happened and asked us what steps could be taken.

Q. *Has pesticide contamination been measured in nearby streams?*
A. No, they haven't. Pesticide determinations have been made in a well which is approximately 100 feet from the present well and no pesticides have been detected in the second well.

Q. *What are levels of DDT, DDE, toxaphene, and so forth, in soils at various depths under natural conditions in agricultural areas not grossly polluted?*
A. This will vary with soils. In general, the downward movement of these materials is very slight. Probably 6 or 8 inches is about the greatest depth you'd expect to find these pesticides in these soil conditions.

Q. *Do you know of any adverse effects upon the owner or the animals in the area?*
A. No, I know of no effects. Even though this is a small farming operation, water has been used for farm animals continually since installation. I say that without further comment, because I'm of the opinion that no analysis was made of any meat animal which left the farm, so there could have been unknown contamination.

Q. *What method was used to separate the organic components from the soil?*
A. The method used was wet sieving.

Q. *Could you discuss that a little more?*
A. I might point out that problems encountered in separating soil sediment for pesticide analysis were much greater than I anticipated at the beginning. In fact, I know of no completely fool-proof method of doing this. Possibly a high-speed centrifuge could be used for this separation.

The sediment was placed in a container of water, and sieved with appropriate size sieves to remove sand and progressively smaller fractions as far as sieving is possible. Because it is not possible to sieve down into the clay fraction, the final separation was attempted by a gravity separation method. The silt and clay fraction was mixed in a container of water, stirred thoroughly, and allowed to set an appropriate time for the settling of the larger particles, after which clay particles were siphoned off in the water fraction. This procedure was repeated six or seven times. Water was then allowed to evaporate from each mixture. I feel that the determination for the silt fraction is probably biased upwards because of an unknown amount of clay which was not dispersed adequately and adhered to the silt particles.

Q. *Max, what was the soil texture, and can you speculate why the silt had more pesticides than the clay?*
A. I think the soil here is a sandy loam. I believe the question as to why the silt contained more pesticide was answered in the discussion on the previous question.

Q. *The data showing vertical movement of pesticide to the well is not very clear. Would you repeat how you know pesticide moved to the well through the ground?*
A. I'm sorry I was not clear on that point. In fact, I did not intend to indicate that pesticide moved vertically through the soil to the well. The pesticide contaminated soil was transferred to the water table and the bottom of the well. This was shown by the soil profile chart which showed backfill material of the same color, texture, and particle size as top soil, and also from pesticide concentrations in top soil as compared to pesticide concentrations in the well sediment. Concerning the downward movement of these materials in the area where the flushing and spraying operation had taken place, I intended to show that only a slight downward movement occurred.

Q. *Max, did you investigate any ionic change which might have caused an increase in chloride in the ground water? Also, have the total dissolved solids been affected?*
A. No, I have not looked at that.

Q. *We have about five questions here concerning the term organoleptically. What is the term organoleptically?*
A. That would be when you have a strange taste or odor present.

Q. *What is the symbol* p,p′ *that you had before the DDT in the abstract? That was probably an error, I imagine.*
A. No, p,p′ is the para para isomer of DDT. DDT is composed of the para para, p,p′, and the ortho para, o,p′, isomers. Commercial grade DDT is composed mainly of the p,p′ isomer with a small portion of the o,p′ isomer.

Gasoline Pollution of a Ground-Water Reservoir — A Case History[a]

by Dennis E. Williams[b] and Dale G. Wilder[c]

ABSTRACT

A leak in a product gasoline pipeline near the City of Los Angeles has caused contamination of a valuable ground-water supply. Since 1968, it is estimated that 250,000 gallons of gasoline have seeped into the underground reservoir, limiting the value of a well field adjacent to the contaminated area.

Remedial measures include extensive analytical studies of the two-fluid flow system as well as an all out effort in the field to try and clean up the gasoline and restore the aquifer to service. The field methods involve an elaborate system of "skimming" wells designed to produce a high gasoline/water ratio and on-site treatment facilities at many locations throughout the area. To date, 50,000 gallons of free gasoline have been removed from the aquifer in this manner.

THE PROBLEM

In September 1968, Forest Lawn Memorial Park (located in the City of Glendale, California) reported pumping free gasoline from one of their large irrigation wells. Upon removal of the production pump they proceeded to pump and bail over 1,000 gallons of free gasoline from the well. A drilling contractor retained by Forest Lawn drilled some 20 small diameter wells in the area in order to determine the quantity and extent of the gasoline. From the results of these first 20 wells it was estimated that approximately 160 thousand square feet of area were influenced with the average depth of free gasoline ranging from 6 to 18 inches. Using an average porosity of 30 percent the volume of free gasoline existing in the reservoir was estimated to be about 250,000 gallons (see Figure 1).

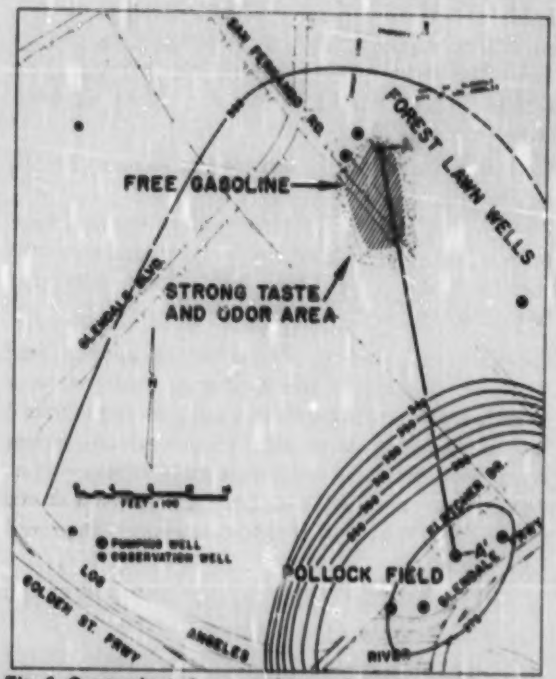

Fig. 1. Contaminated area and ground-water contours, as of 1968.

Shortly after, the Western Oil and Gas Association (referred to as WOGA) was contacted and proceeded with pressure tests of a buried 8-inch gasoline pipeline located in the area in hopes of determining the source and quantity of any leaks. Although initial tests were negative, later test results showed possible evidence of a leak, and flow in the pipeline was immediately terminated. WOGA then initiated an abatement program and proceeded to hire experts with the hope of attaining rapid solutions to the contamination. In November of 1969, the Los Angeles Department of Water and Power turned off its nearby Pollock Well Field to prevent the contamination from migrating into the influence cone of the wells.

Extensive drilling and testing continued in the area under the direction of WOGA to further define the problem. In April, 1969, it was evident that some immediate action had to be taken to prevent contamination of all producing wells in the area. It was decided to concentrate on an intensive drilling and pumping program to control the lateral spread of gasoline.

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

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GEOHYDROLOGY

The area involved is located in the southeast section of the San Fernando Valley where the basin narrows and contacts the coastal plain of Los Angeles. In the Forest Lawn area, the valley is approximately two miles wide and composed mainly of alluvial outwash from the San Gabriel Mountains lying to the north. Sands and gravels interbedded between lenses of silt and clay constitute an important ground-water reservoir.

The ground-water reservoir is bounded by Plutonic basement rocks on the east and northeast, by nonwater-bearing Elysian hill formations to the west and southwest, and nonwater-bearing sediments on the south and southeast. In the immediate Forest Lawn area, the alluvium overlies a basement complex seen outcropping in the hills to the east. Immediately overlying the basement rocks, and underlying the alluvium, is a layer of grey organic clay.

The random nature of the depositional cycles has caused the ground-water flow to be predominantly anisotropic with higher hydraulic conductivities in the direction of alluviation. Interbedded with the sand and gravel deposits are extensive lenses of brown clayey-silt which forms localized barriers (aquitards) to vertical ground-water flow and have created multiple aquifer systems (see Figure 2). The depth of the unconsolidated material ranges from 150 feet to 250 feet deep in the reservoir area.

Aquifer tests conducted in some of the recently drilled wells show hydraulic conductivities ranging from lows of 500 gpd/ft^2 and less in the silty zones, to over 2,000 gpd/ft^2 in the clean sands and gravels. Storativities range from 0.10 to 0.005 suggesting semiconfined aquifers with the confining layers being somewhat leaky. These aquifer test results have been supported by geologic samples and electric logs.

The only significant structural feature in the area is the east-west trending Raymond Fault. The fault displaces bedrock (Figure 2) but as of yet, no evidence of displacement (geologic or hydrologic) in the recent alluvium has been found.

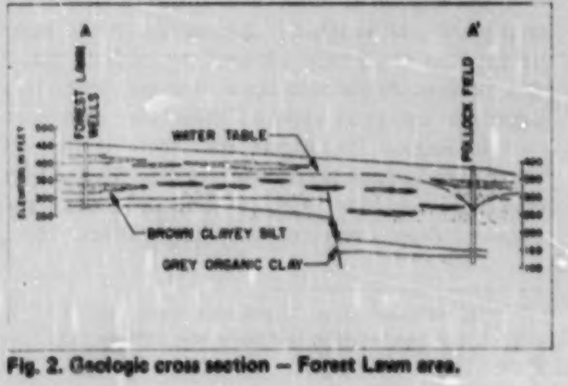

Fig. 2. Geologic cross section – Forest Lawn area.

SOLUTION

Since the original indication of the problem, dating back as far as April 1968, nearly 70 wells have been drilled in an attempt to adequately define the problem and expedite the removal of the gasoline (see Figure 3). Principal removal techniques have included skimming operations using both dual and single completions. In the dual completion technique the lower aquifer was packed off and clean water pumped from this zone while another small pump removed free gasoline and water from the upper contaminated zone above the packer. (The packer in the well provided effective separation for a while; however, the confining layers were either leaky or only locally continuous as gasoline was eventually detected in objectionable amounts from the lower zone.)

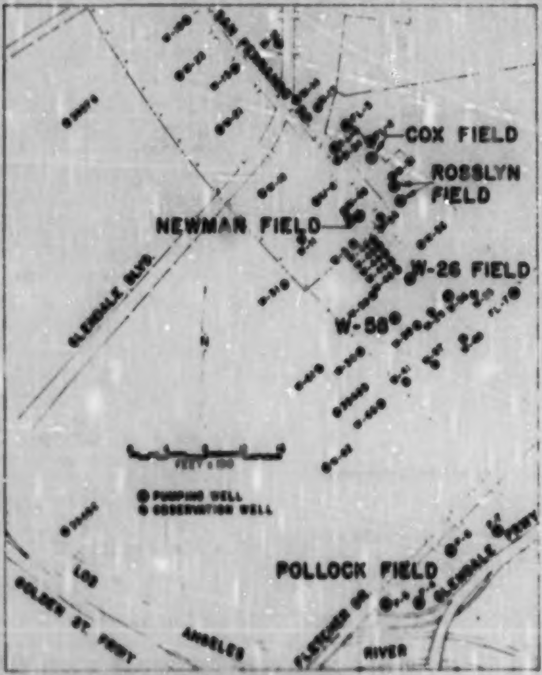

Fig. 3. Pumping and observation wells.

Widespread use was made of the single completion, in which small jet pumps were placed very near the surface of the water to remove the free gasoline layer from the top of the water surface. The skimming wells would then pump into separator tank assemblies located in the area. These separators were composed of density stratification tanks coupled to a larger baffled tank where floatation and skimming, along with aeration in the water progressively separated the gas-water mixture. Free gasoline was then temporarily stored in a separate tank prior to disposal by tank trucks.

During the three years of clean up, over 50,000 gallons of gasoline have been removed from the reservoir. It is believed that most of the free gasoline has been removed, as most of the wells no longer show any measurable amounts of gasoline (see Figure 4).

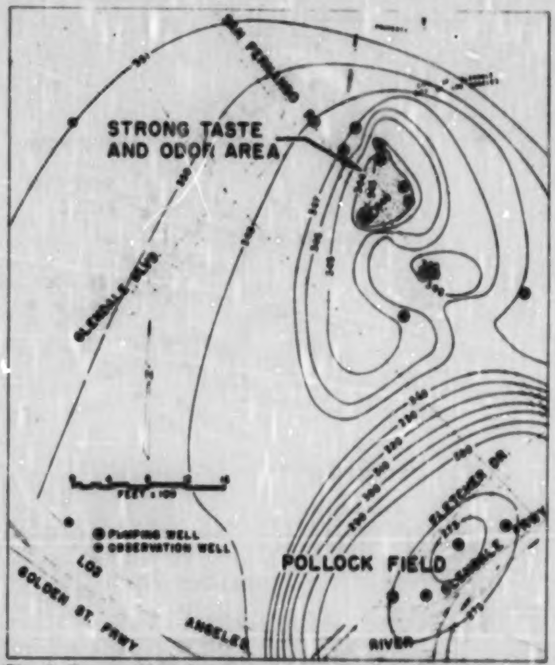

Fig. 4. Contaminated area and ground-water contours, as of 1971.

The possibility that residual gasoline might exist which could not be flushed out with water was recognized long before the clean-up operation was started and the difference between the original free gasoline estimate and the actual amount verified this possibility. It is possible that the lack of data resulted in erroneous first estimates. It will be recalled that in the original estimate a porosity of 30 percent was used in the calculations, while later pumping test results showed effective porosities of 10 percent and less.

The difference between the original 250,000 gallon estimate and the 50,000 gallons removed could also be explained by a reduction in the relative permeability of the gasoline. In immiscible (two fluids) flow, the permeability[1] of the formation to one of these fluids is dependent on the saturation of the other fluid. A relative permeability graph (Figure 5) shows the relationship between the observed permeability of each fluid for various saturations to that of the observed permeability if the sample were 100 percent saturated with that fluid (this permeability ratio is denoted as K_r). The curves shown in Figure 5 are not based on any actual laboratory work done in the Forest Lawn area and cannot be used for quantitative evaluation of the problem. This relative permeability concept is not new and has had widespread use by the oil companies in their production operations.

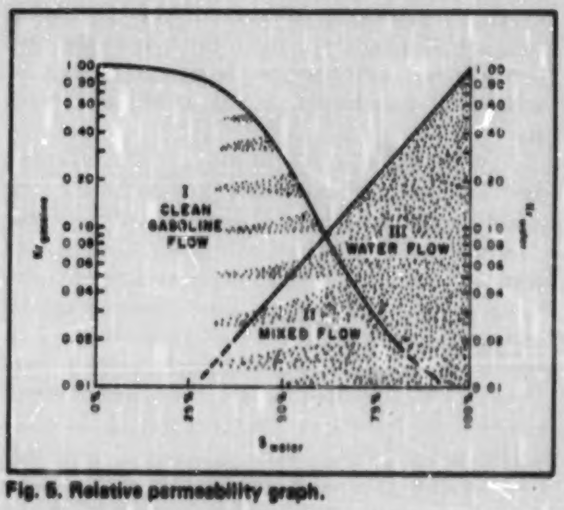

Fig. 5. Relative permeability graph.

The three sections shown in Figure 5 (I, II, III) represent different flow characteristics resulting from different water saturations. In Region I there is a high saturation of gasoline; nearly all the fluid flow is composed of gasoline because it is a continuous phase while water is discontinuous. This results in a low relative permeability to water. Since gasoline is the nonwetting fluid[2], the smaller capillaries will be filled with water (see Figure 6-a).

In Region II both water and gasoline are continuous, although not necessarily in the same pores. This continuity allows flow of both water and gasoline. As the saturation of water increases, a larger percentage of water will flow (see Figure 6-b).

In Region III (Figure 6-c) there is flow of water with little or no flow of gasoline. The smaller capillaries are filled with gasoline only when the pressure drop overcomes capillary forces. Thus,

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[1] Permeability as used here is actually the Hydraulic Conductivity used in ground-water terminology. Due to the large amount of literature in the petroleum field on two-fluid flow, the term permeability instead of hydraulic conductivity is used here for consistency.

[2] If adhesive force > cohesive force then $\theta < 90$ degrees and the liquid is said to be the wetting phase (see Figure 7).

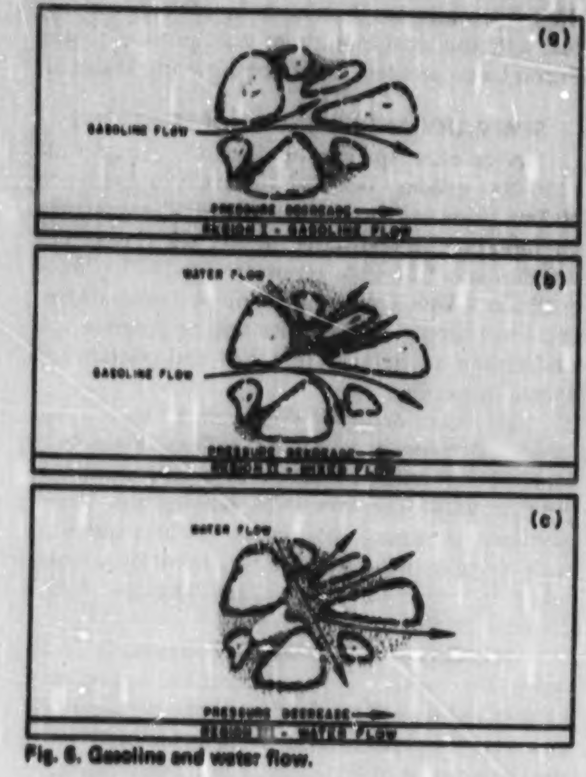

Fig. 6. Gasoline and water flow.

until the pressure drop ($P_{gas} - P_w$) is greater than P_{cap}, it is impossible to move the "snapped off" gasoline bubbles through the throats. As a result, the gasoline does not fill the "neck" or pore throat, and becomes extremely difficult to move. The principle is illustrated in Figure 7 with the following conditions pertaining:

For equilibrium:

$$P_{gas} - P_w = P_{cap} = \frac{2\sigma \cos\theta}{r_c}$$

For movement:

If $P_{gas} - P_w > P_{cap}$	then nonwetting gasoline will displace the water.
If $P_{gas} - P_w < P_{cap}$	then gasoline cannot displace water and therefore cannot move through the capillary but will be forced back until equilibrium is reached.

Where:

P_{cap} = Pressure due to surface energy = $\frac{2\sigma \cos\theta}{r_c}$.

P_W = Pressure on the water side of interface.

P_{gas} = Pressure on the gasoline side of interface.

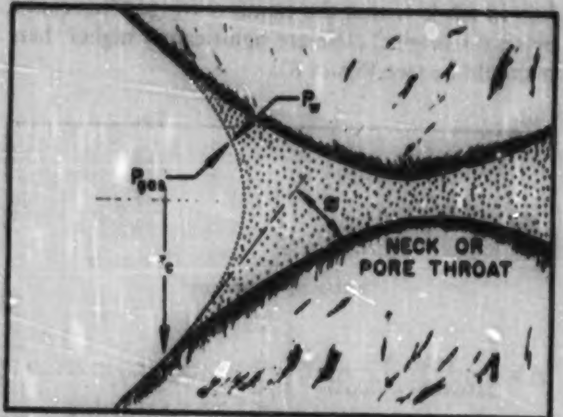

Fig. 7. Pressures on a capillary interface.

σ = Surface energy (a function of the fluids).

θ = Angle of contact between fluid and rock matrix (a function of both rock matrix and fluid).

r_c = Radius of the capillary.

This relative permeability can be both a hindrance to the removal process as well as an aid to producing clean water. Since there will always be some channels or necks which are bigger than others, it is virtually impossible to flush out all the remaining gasoline. The water which is used to flush the sand will tend to flow through unblocked or continuous water-filled channels rather than through the gasoline-blocked channels. Conversely, water which is produced from a contaminated zone may be essentially clean if the gasoline saturation has been reduced to a low level.

This idea has been investigated by Los Angeles Department of Water and Power hydrologists as a means of cleaning the gasoline contaminated water after it has been pumped. In the actual experiment, filter sand was saturated with water and then a gasoline-water emulsion forced through the filter. The ppm of gasoline in the discharge was noticeably lower due to this process.

In addition to the lack of data and reduced relative permeability, another reason for the difference between the estimated spillage and the total recovered gasoline is the mixture of gasoline and water which occurs in the capillary fringe. While the capillary fringe will be compressed somewhat by the head of gasoline, there will still be a zone which contains water held by capillary forces and gasoline which is free to drain. When the depth of "free" gasoline is measured in the well, the thickness of gasoline includes both the depth of gasoline, which is above the fringe, plus the depth of gasoline which is within the capillary fringe. This could make the original estimate significantly higher than it should be (see Figure 8).

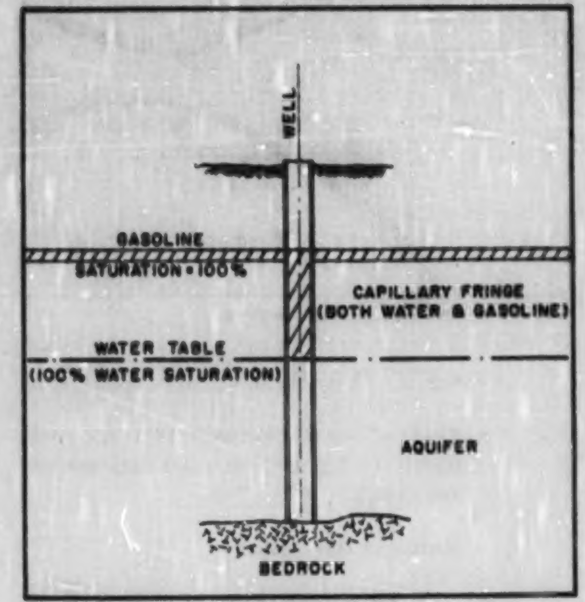

Fig. 8. Gasoline-water table relationships.

The major current problem facing hydrologists and engineers is how to adequately clean the saturated and unsaturated portions of the aquifer of residual gasoline. Of several techniques which have been considered, one of the more promising is to encourage growth of naturally occurring but normally dormant bacteria (principally genus pseudomonas) which have been detected in water samples from the area. These bacteria grow on gasoline and have been noted in wells and separator tanks in the Forest Lawn area.

Preliminary studies indicate that the bacteria convert two thirds of the gasoline to carbon dioxide and one third to new bacteria cells. The process is limited by availability of oxygen, mineral nutrients and gasoline-water interfaces. It is hoped that the bacteria can be utilized to clean the aquifer of the residual gasoline without plugging up the wells and formation with bacterial slime. Work is presently underway by WOGA and petroleum companies to solve this slime problem. Unfortunately most of the work which has been done is not readily available, and the applicability of this process to the Forest Lawn problem cannot be currently analyzed.

SUMMARY AND PRESENT OPERATIONS

A gasoline spillage of significant magnitude (250,000 gallons) occurred in the San Fernando Valley, prior to November 1968, which threatened an important ground-water supply. The City of Los Angeles was forced to terminate production from its Pollock Well Field to prevent contamination of the water supply. An intensive drilling program was undertaken to define the limits and contain the spread of gasoline.

Efforts to drain off the gasoline have resulted in a total recovery of 50,000 gallons of gasoline. Most of the wells now have only a taste or odor of gasoline with only two wells showing any "free" gasoline. At present, operations are at a standstill with biweekly measurements and monthly samples taken in order to monitor any changes in the contamination.

It is hoped that bacteria will eventually break down the residual gasoline so that the aquifer may be restored to service. Studies of the feasibility of this technique are currently being made by WOGA, the Department of Water and Power, and others.

The results of this contamination are very costly. The loss of the Pollock Well Field alone is significant, in addition to the cost of drilling and operating the 70 wells which are required to contain the spill, and drain off the gasoline.

The costs of remedial measures necessary to eliminate the contamination in a problem of this type far outweigh the relatively low costs of preventive maintenance.

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DISCUSSION

The following questions were answered by Dale G. Wilder after delivering his talk entitled "Gasoline Pollution of a Ground-Water Reservoir—A Case History" (coauthored by Dennis E. Williams).

Q. *Dale, we have a two part question here—(1) What is the estimated ground-water volume within the contaminated area? (2) What is the guesstimated volume for clearing the aquifer down to the threshold point for gasoline, considering hydrodynamic dispersion and flow conditions?*

A. On the first question, I'm going to have to hedge a little bit. The title of the paper refers to the problem as "A Case History" which is somewhat misleading because it implies past rather than current history. However, the outcome is not yet known and some information, if it were made public, might influence that outcome. Let me give you just a little bit of the history of this problem. The utilities and companies involved, and there were several, felt that a solution to the problem was urgent; therefore they initiated cleanup and monitoring programs, assuming that they would be able to recover their expenses once the source of pollution was found. It now appears that there possibly will be some sort of litigation or out-of-court bargaining coming up in the future to recover these expenses. For this reason I can't release the estimated ground-water volume or the amounts of money involved.

As far as the volume for clearing the aquifer down to the threshold point for gasoline, I think that the current feeling is that it can't be done solely by pumping of ground water, and this is the reason for stressing the bacteriological approach. The lowest gasoline contamination from the separation facility effluent is about 1 to 2 parts per million which is well above the threshold value, and into the objectionable range.

Q. *We have three questions here. We'll go one at a time. Do you feel that the tank and pipeline test techniques used for routine testing are adequate?*

A. This, once again, gets into one of these problem areas. I think, from what I have read, the test procedures are adequate. However, the interpretation of the results is subject to argument. The procedure used was to pressurize the tank or pipeline and then attempt to inject diesel fuel or some other fluid into it. Any diesel fuel accepted by the tank or pipeline would either indicate leakage or some other problem. The petroleum industry felt that on these particular tests, temperature, compression of entrapped air, and so forth, explained the volumes of diesel fuel used. However, it was felt by many people in the water industry that these tests did show possible leakage.

Q. *Were you satisfied with the test of these facilities after the problem was identified?*

A. I think we were basically satisfied with the second set of tests that were run. The Department of Water and Power sent representatives out to observe the tests, and we were satisfied that this particular test was an adequate test. It was on the basis of this test that the pipeline was closed in.

Q. *What kinds of pumps were used? Were there any special modifications to prevent explosion?*

A. Most of the pumps were air or water operated jet pumps. There were strong odors built up which indicated a possible explosive condition, but to my knowledge, as far as the pumps were concerned, there were no special precautions taken other than shielding of all the electrical wiring.

Q. *Are the pipeline pumping records so poor that a 250,000 gallon loss could go unnoticed, and could the company records be subpoenaed to determine the actual loss?*

A. Let me answer the second part of that first. I think that the records could be subpoenaed. As far as "Are the records this poor," when pinned down, WOGA admitted a 250,000 gallon loss would probably be picked up in the accounting procedures. I don't think that they are willing to admit that there were 250,000 gallons lost. I'm not sure just exactly how much they can detect. They haven't released this figure to us.

Q. *Was any attempt made to identify what company produced the gasoline by chemical analyses?*

A. Yes. There were several tests run and attempts made to identify this gasoline. Unfortunately, contrary to some of the advertisements that the industry puts out, WOGA tells us that they can't pin down the brand of the gasoline strictly by chemical analysis. Originally, they thought that it was several different types of gasoline mixed together; then they felt maybe it was just one type which had been altered in the underground, and so forth. However, they have not been able to identify it, at least to the point that they are willing to admit that they know whose gasoline it is.

Q. *Did soluble components pollute the water all the way to the bottom of the aquifer, or was water from the bottom still drinkable?*

A. It appears that water from the lower portions of the aquifer was clean and able to be used for domestic uses. In the Forest Lawn No. 4 well, I mentioned that they had pumped from the second or the lower part of the aquifer. However, after pumping for a long period of time, it appeared that there was some downward leakage of gasoline into the area. This was somewhat expected based on a viscous model study made by Dr. Williams which assumed that the clay formed a leakage layer and not a solid barrier to fluid flow.

Q. *Has the owner of the product pipeline shared in the cost of removing the gasoline from ground water in the problem area? If not, why not?*
A. Well, I imagine they have, but this information is not officially available to us. WOGA has represented the oil industry, and originally it was fairly common knowledge that the industry as a whole was sharing in the cost. We understand, or at least get the feeling from unofficial sources, that recently one company, specifically Mobil, has been sharing the majority of the cost. However, I know of no official notice as to who is paying the cost other than that monies are coming through WOGA for the industry as a whole. This inability to obtain definite information is one of the problems that you run into with representatives speaking for an industry as a whole.

Q. *Why did you not use activated carbon filters to remove the taste and odor problems after the pure gasoline was removed?*
A. I'm sorry I didn't mention that when I was talking about the sand filter. Activated carbon was tried and found to be much more effective than the filter sand that was talked about. As a result, this was suggested as the means for getting rid of the gasoline in the effluent from the separator tanks. The only attempt that has been made by the Department of Power and Water was where they hooked up a small system to eliminate the gasoline from the separator tank itself. It looked hopeful and was working fine; however, it was a very small, more or less experimental, model. The size of the facility needed would have to be built by WOGA and they are not, to my knowledge at least, willing to do that at this time. They do not feel that it would be economical.

Q. *Has the total cost-to-date of the Forest Lawn problem been estimated?*
A. Part of these costs have been estimated. It is fairly common knowledge that WOGA has spent in the range of $700,000 in their drilling and abatement program. However, the costs incurred by other parties are not available because of possible litigation.

Q. *Did you measure the lead content of the water from the wells?*
A. I'm not really sure of the lead content of the water itself. The content of the gasoline samples was taken and it was found to be high-test ethyl gasoline, but I'm not sure on the water samples. I'm sure that the lead content of the water is measured by our Sanitary Department, but I'm not aware of the results.

Q. *Was consideration given to removal or disposal of gasoline by burning?*
A. I really don't know whether or not they considered burning the gasoline. To my knowledge it wasn't seriously considered.

Q. *Will you inject the gasoline decomposing bacteria through wells, and how far do you expect the bacteria to move?*
A. These bacteria occur naturally in the water itself, so fortunately we won't have to try to inject the bacteria. The biggest problem I think will be to try to get the oxygen and nutrients to the bacteria to let them work on the gasoline, because the bacteria creates a slime which blocks off the oxygen and nutrients.

Q. *What kind of contamination is occurring in the aquifer from Forest Lawn?*
A. Well, basically, the aquifer around the Forest Lawn area is not able to be used at all for water supply at this time. It appears that the pollution at least is under control—that is, we have not picked up any new gasoline contamination. As far as contamination by Forest Lawn itself, they use various chemicals, and it was suggested that the reason the gasoline could not be identified was that there were chemicals from the cemetery mixed in it. However, I think that this was discounted later and, to my knowledge, gasoline is the principal pollutant in the area.

Petroleum Contamination of Ground Water in Maryland[a]

by John R. Matis[b]

ABSTRACT

Petroleum contamination of ground water is a widespread problem that plagues many areas. Historical data collected in Maryland indicates that most counties in the State record cases of this contamination problem annually. Cases in the "hard-rock areas" west of the Fall Zone have the highest frequency of occurrence, in contrast to the Coastal Plain geologic province to the east. In both areas, the problems have been very localized. It is difficult to handle petroleum contamination cases, and the legal implications are very complex. A disturbing factor is that many petroleum fuels do not deteriorate in the ground-water system. Further, the identification of specific petroleum products in ground water is generally not possible with present techniques. An investigation of a particular complaint can often be split into a preliminary phase and a detailed site investigation phase. Once a source of contamination is located, it must be stopped or removed. Since it is virtually impossible to remove the contaminant from the ground water, legal and regulatory problems continue on for months or years after an original complaint.

INTRODUCTION

Petroleum contamination of ground water can be expensive and time consuming for water resources regulatory agencies. Typical of after-the-fact ground-water quality problems, it is reported or defined only after the damage has occurred. County health departments were surveyed in 1971 for information on the subject, and the historical data collected indicate that many homeowners have been troubled with petroleum fuel in their wells in the past.

The geology, geography, and climate of Maryland is similar to other Eastern Seaboard States and as a result, the hydrogeologic principles of petroleum contamination defined here, should apply to other areas. Primarily because of this reason, the American Petroleum Institute was contacted in 1971 for assistance and advice. The API expressed an interest in the problem and indicated that considerable research has been done in Europe on the topic. This report presents guidelines which are applicable for use by water resources management agencies.

THE GEOLOGIC SETTING

The geologic framework of the State of Maryland defines the severity and location of this contamination problem. In general, the Fall Zone, where the Coastal Plain sediments contact hard rocks of the Piedmont, acts as a dividing line in dealing with complaints. The "hard-rock" areas west of the Fall Zone have the highest frequency of cases of petroleum contamination in contrast to the Coastal Plain geologic province to the east (see Figure 1).

From examining the data it would appear that the area around Annapolis has a very high incidence of contamination. However, the presence of State offices in Annapolis and the active county health department staff is reflected in the greater number of cases recorded for Anne Arundel County (12). Also, these statistics include only those cases reported to State agencies and county health departments. Oftentimes, other cases are not reported and individual problems encountered from leaking gasoline station tanks are handled by the company involved. As communication improves between county and State agencies, and the public, more cases will be reported.

In both the hard-rock and Coastal Plain areas, the problems are very localized, and individual cases are often confined to several acres. The difference in frequency of occurrence results from hydrologic factors. Silts and clays in the Coastal Plain sediments, for example, tend to attenuate hydrocarbon fuels that leak from buried tanks and from spills. Also, the high density surface drainage may intercept a great deal of the material before it becomes widely dispersed. And finally, the dilution factor of the ground water in the Coastal Plain is very great.

In the hard-rock areas, ground-water flow is confined to fractures in the rock, and hence flow is channelized to some extent. This means that the contaminant remains more concentrated in the ground water. Secondly, clays and silts are generally absent and attenuation is less important as a controlling process. In general then, the petroleum accumulates in the fractures, which are defined by local geologic structure, and flows in well-defined patterns. In limestone regions, or in other similar hydrologic situations, the potential travel distance of the contaminant would be much greater than in

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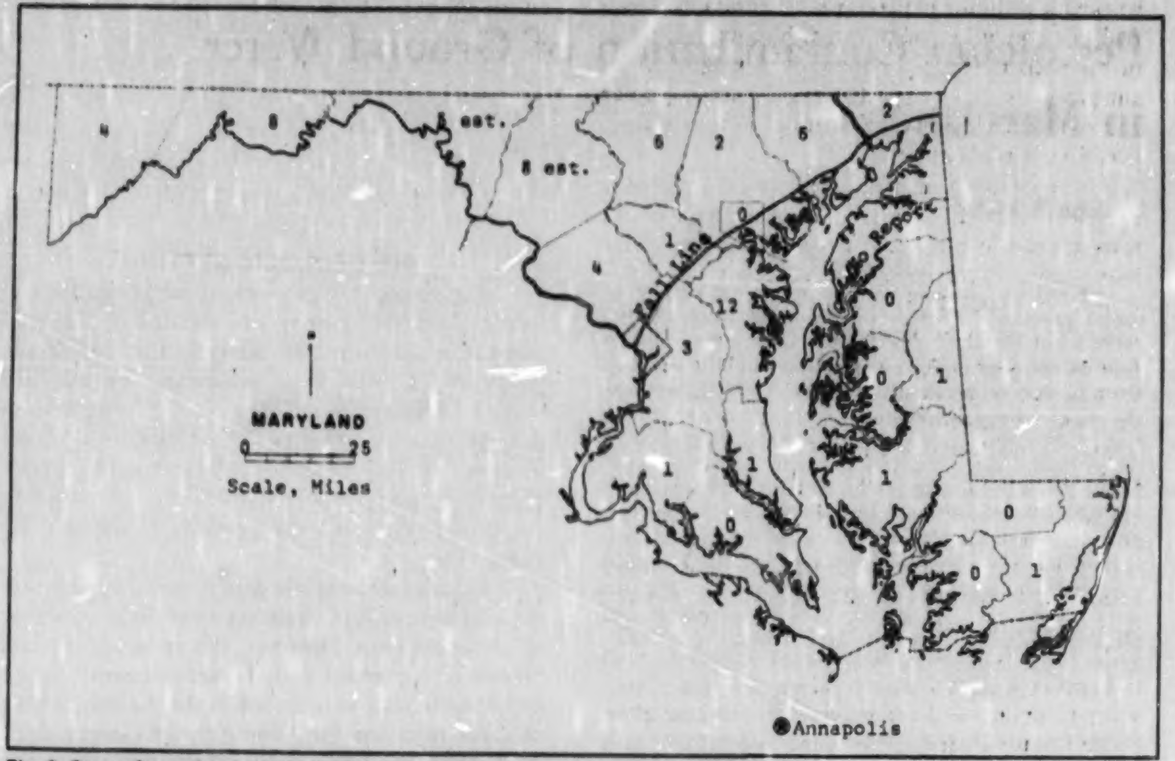

Fig. 1. Cases of petroleum contamination recorded in Maryland counties, 1969-1970.

the Coastal Plain. Likewise, the transit time of the fuel from the source to the well could be much shorter.

COMMENTS AND OBSERVATIONS

Usually a local sanitarian will receive the initial complaint and in Maryland, he then refers it to the Maryland Department of Water Resources. This procedure has developed for several reasons. For example, anyone who has ever tried to define source areas for the petroleum products or who has confronted the aggrieved individual with the contaminated well can testify to the extreme difficulty of handling these cases. The distraught homeowner generally does not understand the nature of the problem or the nature of ground-water flow. As a result, tempers flare and few cases are ever settled to the satisfaction of the aggrieved party(s). Also, the State entered the problem here partly because of the complex legal nature of contamination cases. Expert opinions are needed for adequate settlement, and of course, the State wanted to keep track of any deleterious water quality changes within its domain. Our present position is to define the situation, eliminate the source of contamination, and where appropriate, try to locate an alternate source of water (such as another well site) for the aggrieved party.

The most disturbing and pervasive factor in these cases, is that gasoline and kerosene (low boiling point hydrocarbons) essentially do not deteriorate in the ground-water system (James Grutsch, American Oil, personal communication). Once they reach the water table they remain there indefinitely or until they move out of the area with the ground water. These low boiling point hydrocarbons actually float on the water table at higher concentrations. As a result, any open hole, and particularly a pumping well, tends to act as a hydraulic sink and draws in the material.

Identification of specific petroleum products at the very low concentrations typically found in contaminated wells is generally not possible with present techniques. The infrared spectrophotometer procedure requires at least 1-10 ml. of concentrate. Oftentimes it is virtually impossible to remove this required amount. The gas chromatograph may alternately be used, but it can only identify "low boiling point" or "high boiling point hydrocarbons"—not specific unknowns like gasoline and kerosene. The human threshold for detection of gasoline, however, is 0.005 mg/l and approximately 0.01 mg/l for fuel oil (McKee and Wolf, 1963, p. 230). As a result, you can smell and taste hydrocarbon fuels in water even though you can't detect it on the gas chromatograph.

Of course, high concentrations of particular products resulting from gross contamination can be worked with in the lab and specific products identified. This may be complicated, however, by aging of the fuels in the ground and by mixing of different products. It appears that microbial breakdown and oxidation of some petroleum fuels does occur over long periods of time.

Frequently a contaminated well is sampled in the field, and the contaminant volatilizes before tests are run in the lab. It is very disturbing to the homeowner to receive a negative report in the mail from the State Department of Health or Water Resources when he knows that the water is contaminated. This happens so often in Maryland that we now accept personal taste-odor confirmation by the field investigator at the time of sampling. Any samples actually collected are taken in glass bottles with rubber stoppers. Later in the lab, a microliter syringe can be inserted to draw off vapors for gas chromatograph analysis.

Once a positive result is obtained, the investigation then centers on the location of possible sources. Some cases are very obvious and require little knowledge of hydrology, while others seem unbelievably complex. The ability of the investigator to understand (or at least have a feeling for) ground-water hydrology becomes very important. He must first determine where the contaminant originates and secondly, eliminate the source(s). The following outline lists procedures that might be followed when investigating petroleum contamination cases.

PROCEDURES FOR INVESTIGATION

1. Is the complaint still valid; can the investigator taste or smell contamination in the complainant's ground water; when did the problem start?

a. Does the complainant have any source of petroleum stored on his property?

b. Has any repair been made recently on his water system (possibility of contamination from plumber's tools, etc.)?

c. Has the complainant or anyone else recently spilled petroleum products on his property?

During rainy weather, a rise in the water table may concentrate more petroleum product on the water surface. Or, heavy rains may actually flush more material downward to the ground water. Hence the relationship of rain to the contamination problem should be asked of all parties. Another major point is that ground water flows downgradient under water table conditions. If a series of wells on a slight grade are all contaminated, it is most likely that the source of contamination is upgrade.

2. Go to all nearby houses, garages, etc.

a. First check for the presence of petroleum in the ground water, then essentially repeat as above.

b. Look for sources of petroleum products.

c. Ask about and look for evidence of accidental spillage.

3. Check with all nearby (within several hundred yards) gasoline stations and repeat as above.

a. Identify the full names, addresses and phone numbers of owners and operators, and gasoline distributors for the station(s).

b. Ask for information on storage tanks or pump leaks.

(1) Identify the owner(s) or responsible parties for all buried tanks of any kind.

(2) How long have the tanks been in and have they been checked for leaks recently?

(3) Have the tanks been filled recently? Does this correlate to the appearance of contaminant in the complainant's well?

c. Look at the complete physical layout of the station.

(1) Identify all drains and ditches, both inside and outside the station.

(2) Look for places where oil or gasoline is drained into the ground.

d. Try to determine if any operating procedure contributes to the problem such as:

(1) Throwing waste oil or gasoline out on the ground.

(2) Flushing petroleum products down drains or septic tanks.

(3) Unnecessary spillage of gasoline when filling trucks, filling cars, etc.

(4) Poor storage facilities for old drums full of oil or other petroleum fuels.

(5) Possible spillage by other parties at the station site.

e. Notify the owner or operator that all the tanks and lines should be checked for leaks. (We have observed that leaks from broken buried lines and not from the tanks themselves have caused many gasoline station problems in Maryland. The operator of the station will generally detect such a leak as a loss of gasoline, or as water in his tanks.) Any operating procedures or physical characteristic of the station layout that might contribute to the problem should be changed or altered accordingly. In Maryland we issue a formal pollution complaint to force compliance with these recommendations.

The two main aspects of the service station investigation concern the physical setup of the gasoline station and the operating procedures used at the station. The tanks and lines generally constitute the parent oil company's property, and are their responsibility. Other physical aspects of the station (i. e. drains, pits, storage areas, the building) may or may not be owned by the parent company. Any operational procedures are the responsibility of the owner and/or operator of the station.

After all the above have been considered and no leak or source is found, the investigator can probably conclude that the gasoline station is not the source of contamination.

4. Recheck the local area, from house to house, to church, to repair shop, etc., and try to find the source.

5. Request a more detailed investigation if this final check fails to uncover a source. Other considerations, such as the complexity of the situation might also warrant a more detailed study.

This procedure may seem unduly complex, but it is important to try to define the limits of contamination. Some people, particularly those who are old or very poor, may be reluctant to admit that they have a contaminated well. They fear that the health department may condemn their water supply or that they will become involved in a costly lawsuit. The field investigator must allay their fears and obtain accurate information.

DETAILED SITE INVESTIGATION

In spite of these time consuming and detailed procedures, a hydrogeologist will frequently have to make a field inspection to determine the source(s) of contamination. In many cases, several possible sources may be identified, although in other cases, the initial overview may disclose no possible sources. In one such instance in Maryland, vandals apparently dumped oil down a homeowner's well. To pinpoint an exact source, however, sometimes a test drilling program is required. For this purpose in Maryland, we use an auger drilling rig.

The Groundwater Management Division receives the preliminary data and conclusions (or questions) of the field investigator. Upon recommendation from him, we then proceed with a more detailed site inspection. Initially we attempt to visually determine the ground-water flow at the site. We may be able to quickly locate sources of contamination or define the contaminated area. If auger drilling is required, we drill shallow holes through the weathered rock or sediments to the water table. During the drilling, soil samples are collected for analysis and inspected by the hydrogeologist in the field. A plastic pipe or casing can be inserted in the hole to let the water collect. The water in the pipe is sampled and analyzed. Eventually, "positive" data points may define a source, such as a buried tank. It is significant to note that the expense involved in test drilling often precludes this technique as a routine investigatory tool.

Once it is located, the source of contamination must be stopped or removed. Maryland law allows us to issue a formal pollution order which requires compliance with our findings and recommendations. If the situation warrants it, we may also advise the aggrieved party to seek legal counsel.

OTHER CONTROLLING FACTORS

Since the configuration of the water table generally reflects topography, most gasoline contamination cases can be easily defined. In one interesting case, however, it appeared that a hard clay layer in the weathered rock zone prevented downward movement of gasoline from a nearby service station. Spilled gasoline probably moved on the top of this hard red clay, and then was intercepted by nearby wells penetrating it.

Disturbed ground may be more permeable than surrounding native rock and sediments. Because of its higher permeability, it may intercept and channelize contaminants. Northeast of Baltimore a buried continental pipeline developed a severe leak, but all of the gasoline remained in the disturbed fill around the line. Where the pipeline crossed a small stream, however, the fuel seeped out and, of course, became obvious as it floated downstream.

In another case a buried tile foundation drain intercepted and concentrated sizable amounts of gasoline and Number 2 diesel fuel. Both of these fuels were present in the ground at the building site, probably the result of a gasoline station leak at some time in the past. The flammable materials and fumes in the sump pit created an explosion hazard near the building, and only after modifying the drain system considerably was the problem brought under control. The first concern in this instance was to remove or lessen the hazard. Concurrently, efforts were made to separate the gasoline from the discharging water. However, the discharge of gasoline to the city storm drains was avoided because it also created a potential explosion hazard. Pockets of fuel might have collected in low spots in the storm drain system, and invited a disaster.

The integrity of the wells in a petroleum contaminated area also seems to have an influence on the occurrence of well contamination. A longer length of casing and a good grouting job may save some homeowners from problems of this sort. Of course, in the Coastal Plain a new well could be drilled to another aquifer in an uncontaminated zone.

Over a period of time pumping may remove some of the contaminant. Although we have advised the use of this technique for cases of minor contamination, it has not definitely proven successful. An activated carbon water filtering system can also remove some types of petroleum fuels at very low concentrations. However, in Maryland we are not aware of any water conditioning equipment that can remove significant amounts of petroleum contaminant.

Occasionally the petroleum contaminant may move out of the area or be sufficiently dispersed so that it can no longer be tasted in the water. The aggrieved parties have then been advised to use the water. In general, water that is only slightly contaminated by petroleum fuels is not toxic to humans. By the time the concentration reaches a toxic level, no one would be able to stand the smell or be able to drink it (McKee and Wolf, 1963, p. 230).

CONCLUSIONS

To summarize, the impact of the problem on ground-water management in Maryland is greater than had been expected. Each case requires at least one day in the field by an investigator and frequently by a hydrogeologist as well. Figure 1 indicates that in 1969-1970 over 60 cases were recorded by county health departments and Maryland Department of Water Resources personnel. County health department sanitarians also contacted many of the people involved and collected water samples. As a result, the problem has consumed a large number of man hours.

Fortunately to date, all of the cases we have handled have been settled out of court. It is conceivable, however, that the investigating hydrogeologist may eventually have to appear in court as an expert witness to discuss the findings of his investigation. Hence the obligation to present a factual definition of the hydrologic environment is critical. With regard to clean-up activities, it may be (and often is) impossible to remove the contaminant from the ground water. This presents interesting, if not continuing legal implications.

It seems that the more cases you handle successfully, the more you receive for action. The problem has not been given priority in the past, but will be handled more directly in the future.

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DISCUSSION

The following questions were answered by John R. Matis after delivering his talk entitled "Petroleum Contamination of Ground Water in Maryland."

Q. *In a group of service stations, what method do you recommend to determine which of the gasoline stations' tanks is leaking? In other words, how do you differentiate one from a group of many?*

A. You have asked a significant question. There is no good way at the present time, as the previous speaker indicated, to determine the gasoline from, say a Mobil Oil station or a Texaco station or an ESSO station, in a typical contaminated water supply. Additives are used to identify a particular company's product. If the petroleum contaminant occurs in the parts per million range, and the additives occur at a parts per million of that, the problem is obvious. These additives would therefore occur at extremely low concentrations in contaminated ground water. Hence it would be impossible to detect them and differentiate gasolines. As far as locating a source, we would suggest a test hole drilling program, and leak testing of all tanks and lines.

Q. *Undoubtedly, the use of various storage tanks is increasing with the increase in auto population. Is there any feasible preventative maintenance program that will enable the owner or regulatory agency to predict the probable onset of tank leakage as the tanks age?*

A. The idea of a preventative maintenance program deserves more attention by the petroleum companies. There are many factors which determine why a tank leaks. Some tanks, for example, have been dug up and the tar coating on the outside is just as fresh as when it was buried. However, it is becoming increasingly obvious—because of contamination and the dollar suits involved—that some oil distributors are going to Fiberglas lined tanks which do not deteriorate, and I think that this is one of the answers we have at the present time. Perhaps some changes in the construction of buried lines would also be desirable.

Q. *Are your efforts, in part, responsible for the popularity of Fiberglas TOL tanks and piping?*

A. I'm sure our efforts are not the total effort involved. Research people in the petroleum industry have said that they are limited because they operate under an economic condition. In other words, changes in tank construction and development of new identification techniques cost money. These changes cannot be made without sufficient documentation. So our documentation probably helps their programs along.

Bull Session 2—Chemical Contamination of Ground Water

Session Chairman: Allen Agnew, Director, State of Washington Water Research Center, Pullman, Washington 99163.

Allen Agnew, Lead Bull:

Gentlemen, we are going to operate with two mikes tonight. As you know, this is all being recorded, so when you speak please bear this in mind and identify yourself each time. I am Allen Agnew, not Bill Cawley who, as you know, is unable to be here. Yesterday afternoon, Bob Crowe filled in for him, and I am filling in for him tonight.

You remember our session consisted of four speakers, one who was unable to speak, but had presented an abstract earlier, for our use. In discussing ground-water pollution, we talked about pesticides, gasoline, and petroleum in general. We had some unanswered questions. I would like to open this discussion by asking Dale Wilder if he has anything further to say in elaboration of what he said or in response to questions he received this afternoon.

Dale Wilder, Hydrologic Engineer, Los Angeles Department of Water and Power:

The only comment I had was that there had been some discussion after both my paper and John Matis's paper, in relation to whether or not the petroleum products can be identified by laboratory analysis. It appears from comments of at least two or three individuals that there are some laboratories that feel they can analyze petroleum products as to brand, type and even possibly area that they were produced from, depending upon the type of sample they are given and whether or not they have a good standard to compare with.

Of course, there was also one other comment that was brought up when John and I were talking—that is, we might be able to use radioactive tracers to inject in underground storage tank leaks and pipeline leaks to monitor them. The problem that we could see with this particular technique is the public hazard and the public pressure involved.

Just as a way of comment, we had a reservoir in Owens Valley, California, that appeared to be leaking. We had some drains about a quarter of a mile away from the reservoir, and had been picking up quite a bit of water flow in them. The Hydrology Section wanted to account for that water and they didn't want to double-budget it, so they were wondering how we could actually find out if this water was coming from the reservoir or if it was coming through a basalt area to the east of the reservoir. We considered running radioactive material and finally gave up on this particular approach, for the very same reason that I think the same approach would be difficult in the business of trying to find oil leakage.

There is no build-up of population at all in this area. The valley is owned jointly by several people, but the Los Angeles Department of Water and Power owns most of the valley floor; they bought it up several years ago to obtain the water rights. So, it is not a problem of who owns the land or a problem of people living there, but it is a problem because the water eventually gets down to Los Angeles and, even though the half-life may be sufficient that the radioactivity would already be dissipated before it reached Los Angeles, it was feared that the public in Los Angeles would be very sensitive to this. We've tried dyes very unsuccessfully.

Jay Lehr, Executive Director, NWWA, Columbus, Ohio:

I've been wondering—listening to John's paper on gasoline contamination and yours on petroleum contamination—how serious a problem this is on a nation-wide scale. Are we just talking about more of an odd-ball situation? I mean, John talks about something like 60 cases in the State of Maryland. Well, that's not too many, and they affected seemingly very few people. Your situation in Los Angeles, of course, was an enormous problem but, again, it was accident in the nature of an off-shore oil spill. How really significant is this kind of problem in ground-water development, nationwide? Also I can bring in Lewallen's paper on pesticides—he almost went so far as to say that in an area where the pesticide contamination was prevalent, it wasn't that serious. I'm wondering if things are as bad as we thought they were.

Dale Wilder:

In relation to a couple of questions that you asked, I originally felt that the gasoline spillage was probably a rather isolated case. But, in talking to a few individuals, I find that maybe it is a little more common than I realized. As far as actual numbers are concerned, I can't give you a real handle on this, but I have a request already from one individual (who wasn't able to make the conference) for a copy of the paper; he feels that he has the same problem in Ohio. There are similar problems mentioned throughout the nation, although they are isolated cases, as far as I know.

In relation to whether or not this may be similar to the pesticide problem where it is not all that critical, I think that this would depend quite a bit on the individual case. In our case, it was a very great problem. We did have to close down a well field, and Forest Lawn has had to buy water, rather than use their own water. However, there is some possibility, that after the initial flushing took place, we may have suffered no damage other than objectionable taste. That is, the water may be contaminated, but it may be possible to clear it up through the use of some sort of filtration system, such as activated charcoal. Now, one of the reasons I feel that WOGA (Western Oil and Gas Association) did not go to the activated charcoal in their separator facilities was basically economics. The estimates were that it would cost somewhere around $90 per acre-foot to clean this up by activated charcoal. We can buy that water for around $50-$60 per acre-foot so they felt it was better just to replace that water.

Now, this isn't getting into the safety aspect. What do you do with the gasoline and water mixture, when from a purely economic standpoint it may be less costly just to ignore that particular water resource and try to use some other resource? If we were in a really bad pinch, like we may possibly get in because of the recent California earthquake, and because of other losses of water supply, then maybe this would be a much greater problem than it is today. Right now, from a practical viewpoint, we probably can work around it but, from a standpoint of contamination, I think it is a serious problem.

Dick Rhindress, Pennsylvania Department of Environmental Resources, Harrisburg, Pennsylvania:

I, too, have a very similar problem to yours in California, but mine is in Pennsylvania. I think I should respond to a number of the questions that have been asked already. On identification of the product as free gasoline, we have a little different situation because we can just bail it up in a bailer. We have been able to go right to the brand of the gasoline and, in fact, mix several grades and brands of gasoline together to get the precise combination we have on the ground. It was slightly trial and error, but on the gas chromatograph, infrared and ultraviolet tests, we can come up with precisely the same curve. It's fantastic how close it is, in fact.

In cases where we've had just extractable amounts—something we've extracted from basically a water sample, we have been able to say that this is gasoline or this is fuel oil. On a couple of occasions we have come close to being able to say a product name, but we haven't been able to really pin down a specific product. We've been able to exclude some. For instance, we've been able to say in one case where there are two pipelines involved, that it's not the Esso pipeline, but it is one of the products that the Sun pipeline happens to be carrying. But, exactly which of the Sun products we can't determine.

On the subject of radioactive tracers, we have tossed this around, as well. We've come up with the same problem of public acceptance of radioactive tracers. . .we just forgot the idea right there. We have, however, been thinking about using some of the isotope tracers which are not radioactive. We gave this thought to the oil companies—we have two pipelines and three companies involved in our worst problem—but they refused absolutely saying, "we don't want any contaminant in our products." Now this, of course, would be in the parts per billion range, but it was a contaminant to their oil and they didn't want it because they had a marketing product and they said this would foul up their marketing if it ever got to the public. Because all actions taken by our department are public, if we recommended and asked for this, it would be public knowledge that these oil companies had accepted it.

Jay asked about the significance nation-wide. In Maryland there is a report of about 60 spills. I can put my hands on about nine major ones in Pennsylvania, one of which is to the point where we've had explosions in two houses. Thank God, no one has been hurt, yet. We've had people evacuated from their homes because of liquid, free gasoline that's flowing into their cellars. In the latest instance, the people were out for 4 or 5 months. This was because the gasoline pool was in a karst aquifer in the Great Valley of Pennsylvania, and it just rises up every time we have a rainfall.

I received a call tonight that we have a hurricane headed up the coast and I'm supposed to be home in case something happens. That's where we live.

On the charcoal filtration thought, we also propose charcoal filtration in practically every case around the State, where we have the individual gas stations polluting an individual well. Usually, it doesn't work. The economics are just too much at the gas station-distributor level. The oil company does not stand behind the continued use of the charcoal filter—they just won't go into a long-term economic responsibility like that. The people who own the home either drill a new well, try a charcoal filter for a while, give up and then just start boiling water to get the hydrocarbons to volatilize, or bring in water from a neighbor's for drinking and use the oily water for showers and so forth. Charcoal filters just don't work because of economics.

Mike Bell, North Carolina State Board of Health, Greenville, North Carolina:

I wanted to reply to Jay's question about the seriousness of gasoline contamination. I don't know about it on a national scale. I had one experience where a town of about 400 people had a well contaminated; we traced it down finally to a build-up of cleaning fluid and waste oil that a garage had been dumping into a ditch. It traveled some 225 feet through the ground and contaminated the town well. This town, if they had not had some back-up wells, would have been completely out of water. As a result, they did have to rely on an old well which had not been abandoned, but had almost been discarded because of mineral quality. So, we would have a serious problem without these back-up wells and we were quite concerned about the loss of this well. This is one instance which was very serious; I wouldn't be surprised to see this happening in other places because of the lack of concern that's been shown so far.

Allen Agnew:

That is a good comment, and it is one that I had hoped would come up tonight. That is, the deliberate or careless washing down of the filling-station areas into the city drainage system and, where there's infiltration of recharge from this system, we are getting pollutants into our ground water. Where it isn't going into the ground water, it's going into the surface water and so it is a problem of the integrated hydrology of the two types of water.

Ben Wilmoth, EPA, Wheeling, West Virginia:

During the past year, I've talked with State sanitarians who have investigated several fuel oil contamination problems in consolidated rocks. In some cases, the contamination traveled as much as 300 feet in sandstone or shale. Then there was one of these fuel oil problems with a school, in which the fuel oil tank probably contaminated the well at the school—probably caused by overfilling. I don't know how much was spilled, but apparently it doesn't take too much to result in a problem. Another case—a thousand gallons of gasoline leaked from a corroded buried tank and contaminated a school well 300 feet away; this was also in consolidated rock, sandstone. In the Ohio River Valley, petroleum chemicals from a tank-car siding contaminated a municipal water supply; they were able to alleviate this by aeration, but not completely eliminate it.

Verne Farmer, Humble Oil and Refining Co., Houston, Texas:

Several people here have observed specific instances and suggestions of instances of pollution by oil and gas. For about the last year I've been trying to make an inventory of many various types of hydrocarbon spills into the soils and groundwater systems, but my efforts haven't really come to much. Does anyone here know of any such inventory, or systematic collection of incidents that has been assembled—perhaps by the U.S.G.S. or by a State agency?

The API several months ago conducted a survey among its members, most of whom are the middle size and bigger oil companies, asking for case histories and examples of spills that these people had experienced. They got some 110 replies but most of these were the bigger examples, the more spectacular types of things, and in my opinion don't even begin to represent a true, systematic inventory. My interest in this, really, is that Humble—along with most other major companies—is pretty sincerely interested in trying to do everything we can to both avoid and clean up these spills whenever they do occur. Really what we need, more than anything else, are precedents—history and experience with a large variety of these things. We have a lot of dope on the big ones like Forest Lawn, Mechanicsburg, and Savannah, but those aren't typical. Ones where 8 or 10 or 15 individual wells may get polluted, these are more common. And most of these things don't get a lot of publicity. It's a local thing and that's about the end of it. If anyone has any thoughts on approaches or methodology for handling these things, I would certainly welcome them.

Allen Agnew:

Mr. Farmer, in your survey, did you tackle the organization of State sanitary engineers, the State Board of Health people? These are the people who not only have the information within the States, but they get together annually to compare notes and complain about inadequacies in the system, so I would think they would be a good source.

Verne Farmer:

It could be. This really wasn't a systematic survey in the sense that I wrote to representatives in all 50 States asking them for cases of this kind. This was a hit-or-miss sort of thing. I talked to about everybody that I could find, various agencies and various States. My experience with this sampling—which was certainly not complete—was that not very many people knew anything about it at all. And I just assumed that probably this was typical of what you would get if you ran a 50-State survey, which I confess I did not.

Allen Agnew:

We have at least one State agency man here, maybe more—and I don't want to throw the heat on him, but I think that maybe he is in a spot to respond to this.

Dick Rhindress:

I am in a spot to respond to this. Companies which we are working with on petroleum product clean-up do not even notify us of other spills and ground-water contamination problems which they are having elsewhere in the State.

To the second part of the point that was made about contacting a State sanitary engineer, I'm not sure it would do much good. The regional people in our Health Department don't get the word to the central office. They try to handle it on their own. They don't even call in the geologists that they know they have, to help them with it. This is a problem we have and I'm sure other States have it. The regional sanitarian who is a county man, or maybe even at the township level, just does not use the facilities of his professional help at the top level, and the word will never get to the State sanitary engineer. There's a break in the chain-of-command in Pennsylvania—I know it exists in other States as well. It's a nice idea to ask him, but I know the man personally—I work with him—and he just doesn't know about them except what I tell him on the way home from work—not through an official channel.

Allen Agnew:

It seems to me that we need to have a focus for our communication, and what is the focus? Well, to me it seems that it would have to be the man at the State level—the man who is responsible, and if there is a breakdown in the internal communication, we've got to rectify that. Because until that is done, we're going to be sitting on two sides of the fence griping at each other about each one not doing his job. So I think we need to do a lot of homework inside the State among the different layers of government to clean up this inadequate communication pipeline.

Elmer Jones, Agricultural Engineer, Department of Agriculture, Beltsville, Maryland:

This problem is bigger than one can see, because people can have petroleum products in their well and be totally unaware of it if the proper conditions exist—if the production zone is at the lower part of the well and the pump is deeply submerged and there is no water entering the upper casing so that turbulent entrainment of the lighter petroleum fractions might carry them down to the pump.

In pumping sediment from the bottom of a well for pesticide analysis, we obtained a large amount of a jelly-like substance; the owners of the well admitted to having a fuel oil leak several years prior to this, about 120 feet from the well. But they very strongly maintained that at no time had they been aware of any petroleum product in the well by taste, odor, or by seeing it as a thin film on standing water.

I was concerned whether plastic pipe would be a potential health hazard, in that something would be extractable from the petroleum—gasoline or more solvent materials. Normal drinking water would not extract such material from the pipe, but such an accidental exposure should be considered in considering selection criteria for plastic pipe. Floyd Taylor, of the Public Health Service, serves on one of the building research advisory boards on plastic pipe. Floyd has, in the Public Health Service interstate-carrier drinking-water program, investigated several gasoline spills; the feeling of the PHS is that basically such a spill does not represent a health hazard because normally it is possible to construct wells cased and grouted through the surface layer so that you can still obtain water of good quality. This is not to defend the spill, but to indicate that where this is a serious problem, well construction should be taken into account.

Now, you can turn it around and look at it the other way—say, a fuel truck driver accidentally mistakes the upper casing terminal of the well for the entrance to the fuel oil tank, and dumps fuel oil down the well. Here is a case where you would really like to have a fully constructed well that is not cased to below the water table, because when the well is cased to below the water table and you force fuel oil down it, the oil will come out the bottom of the casing, rise to the water surface, and go on to some other point where it can continue to be a problem. So, the point of injection can be cleaned up rapidly, but the well does not permit the removal of the oil at the point of injection.

Dale Wilder:

There are a couple of things that I wanted to comment on. One was in relation to the problem of having spills that go unrecorded and repaired. Basically, my comment is that we need to encourage corporate citizenship — we must make people understand that it is really important to be a good corporate citizen. To give you a small example, when I was working offshore, in the old days they got a little bit calloused about what they did with some of their petroleum products during the testing of some of these wells and, if a barrel or two went overboard, they worried about it but not enough to make them stop operations because of the economics involved in getting out a barge with a tank on it. This isn't all the fault of tool pushers or of all the people in the field, but this did happen.

After the environmental push began and we were notified that such things were to be stopped, the word went around that there was to be no dumping overboard of any empty barrels having a little bit of crude oil left in them, or anything like this. However, this didn't really solve the problem until they told us that the tool pusher, any engineer, etc. would be responsible and subject to fine and jail. Of course, I think you realize that if I was out on the platform and saw a man about to dump a barrel overboard, I would run and get the tool pusher and tell him that this man was about to dump some oil. I would do this because it means something to me personally. I think that once the company really emphasized it and this went down the line, it would work. This is the thing we have to do with the State agency. We need to get the thing started from the top and work it on down.

One other comment in relation to radioactive isotope tracing—I wonder if it might be possible to somehow either heat up the petroleum product, or cool it down, then run a temperature survey.

Harry LeGrand, U. S. Geological Survey, Raleigh, North Carolina:

I was impressed with the contrast between Dale Wilder's and John Matis's presentations. Dale was concerned with a fairly large, extensively used aquifer, whereas John was concerned with a number of little problems in fairly impermeable situations—perhaps you'd still call them aquifers. Maybe we should analyze this particular contrast. I think that if a water-table aquifer is fairly extensive, if it is fairly permeable and is used extensively, then you will have a single large problem, such as Dale described. On the other hand, the Maryland situation for the most part was in the Piedmont Region where the permeability is quite low. Wells are productive for domestic purposes and also in the valley and ridge area, it's the same way. But there are multiple little problems in those regions and in all probability the ground is more contaminated than we think; we just hear about specific problems. There's no question about Dale's problem, it will arise and we can see it. But, certainly, beneath some of our big cities—Denver, Washington, and others—the water-table system, whether we call it an aquifer or not, is certainly polluted from petroleum products and gunk of all types in many different ways and, in many of those places, we don't even use the water anyway. I don't know whether we should say that we dedicate that ground for uses other than drinking water, but I think the number of problems we see is really a question of the number of complaints we hear.

Allen Agnew:

Do we have any further thoughts along this line? I have another question that might take us away from this theme.

Verne Farmer:

I just want to make one observation about this effect of gasoline, or any hydrocarbon, in contaminating ground water and how far down it will contaminate. As you people may know, there's been really a considerable amount of research—lab-type work and field work—done on this subject in Europe, an awful lot more than has been done in the United States. And, actually, a great deal of this stuff has never been translated into English, unfortunately. I've seen some translations of some of these articles in the last few months; most of it is in German. I don't know what the mechanics might be, but I think that it would be very useful for translations to be made available to any association or groups such as this one, that are vitally concerned with ground water.

I think it has been demonstrated pretty conclusively that one of the biggest problems of the light hydrocarbons, particularly gasoline, is the solubility of a lot of the components. Generally, the heavier the product, the less solubles it contains, but by the time you get up to the gasoline range, it has a lot of stuff that is soluble and, if you end up with a body of gasoline on the surface it will float. However, over a relatively short period of time, these solubles will disperse downward and soon contaminate this whole system. And that, in some of the instances I have encountered, has really been the greatest problem. We know where the surface of the water is and, if money is no object and the oil hasn't spread too far, we can clean that off pretty well. But, if you have these contaminants dissolved and diffused completely through the whole system, there's no way to get that stuff out other than to produce the entire body of water in area. Now, that type of thing is quite easily cleaned up with activated charcoal filters, but, as Dick said, sometimes getting those things installed and getting somebody to maintain them is the biggest problem. However, it can be done—there is no question about that. But that solution of certain components of gasoline is, in my experience, one of the biggest problems of gasoline contamination that we have.

Dick Rhindress:

I'd like to state at this time that the Pennsylvania Department of Environmental Resources has just started to plan a seminar. We hope to hold it early next year, next March or April, for people who have dealt specifically with the hydrocarbon clean-up job. We want to get together the people who have really worked in the field on clean-up of gasoline and fuel oil in the ground. We are not, at this point, considering the prevention aspects, but are just talking about the clean-up aspects. I would like some input from anyone who is involved with this sort of thing, as to whether they feel such a program or seminar should involve also the prevention aspects. This seminar will be announced in journals like *Ground Water*. I'd be very happy to hear from anyone who has this kind of problem or can give me some ideas on what we should discuss and how the program should be handled. The basic concept, though, is to keep it at a working man's level, not a formal paper and esoteric discussion level.

Allen Agnew:

We need a lot more of that—a lot more of the hard exchange of ideas by working stiffs—those of us who get the dirt under our fingernails. Gentlemen, we've been bearing down pretty hard on hydrocarbons and, as you recognized, we did have a little bit of exposure to pesticides in the talks during the last two days. I wonder if we might have any reactions or any thoughts along that line.

Max Lewallen, Agricultural Engineer, U. S. Department of Agriculture, Watkinsville, Georgia:

I don't have anything in particular to say about the pesticide problem. I am available to answer questions from the floor if anyone has anything to add.

Mike Bell :

I do have one question, or it may be a series of questions, dealing with the behavior or the movement of pesticides in a tight clay soil. I've heard different comments about the movement of DDT, the adsorption of DDT on clay, and the movement of organophosphates. I'll ask Max Lewallen in particular, since he was the speaker on pesticides, but I'd also like any information from anybody else on the movement of pesticides in general, or on a specific pesticide in a tight clay soil.

Max Lewallen:

The literature is fairly full—quite a bit of work has been done, there's quite a bit being done, and yet there's lots more to be done. I think, as you pointed out in general, that this type of material is going to adhere tightly to the clay portion of the soil. One thing I might add—some of my associates at work, who have been involved for several years with runoff from agricultural lands, laughingly say now that runoff is a new ball game because of past measurements having been made on total runoff quantities instead of this being fractionated in an attempt to correlate the more active portions of the soil, and the clay portion in particular, to the transport of these materials. I don't have anything in particular to say about what you asked. I do say that in general these hydrocarbons will be tightly bound to the clays. It's going to depend by and large on what happens to the clay particle itself.

Mike Bell:

Let me just give you a specific instance on which I was basing this question. As a result of a fire of a storage area for both fertilizers and all types of agricultural chemicals, we experienced a problem of what to do with both solid wastes and a liquid waste. And we ended up putting both the solid waste and the liquid waste in a landfill. This landfill was above the water table and was enclosed in a natural clay area. What I was concerned with is the danger to the ground water. Should we be concerned with movement in soils like this or are we pretty safe in what we did?

Max Lewallen:

I think as far as the larger quantities of pesticides are concerned, such as you refer to, this has not been described adequately in the literature. I know of several groups that are interested in this aspect of pesticide disposal right now. Perhaps you should talk with some of the people like John Matis here from Maryland who is wondering how to get rid of many pounds and gallons of these source materials, along with lots of other people. This is an unanswered question right now, I think. In general, in a clay soil such as you refer to, I still personally expect very little movement of these materials—if we're talking about reasonable quantities—and I don't know myself what I'm referring to by "reasonable quantities." But as far as large doses are concerned, I don't know if anyone knows what will eventually happen to these materials.

Dick Rhindress:

I can only cite one instance of major disposal of chlorinated hydrocarbons—in the Province of Ontario. When Canada outlawed them, they collected all DDT and associated things that they had outlawed, and stuck them underground beneath a large lagoon. The lagoon, to the best of my knowledge is not impervious—rather, it drips out through the bottom. These pesticides were not encased in anything special, and apparently these eventually are going to flush into the ground-water flow regime. The lagoon was in glacial tills that they felt were fairly tight. They didn't have a geologist on the job—at least I've been told this by some Canadian geologist friends of mine who are very concerned about this situation. It sounds like one of the worst possible things that can be done, except that it sits there in the middle of an industrial complex where nobody is using ground water. Boy, if the containers rot off and it all goes into the ground water in one slug, it could really do a job of pollution on whatever river or stream is adjacent. It sounds like the worst possible way of handling them.

Max Lewallen:

A point worth noting here, I believe, is the term that is thrown around in the literature—the half-life of these materials. I don't believe that this term is valid in most cases, but rather it is valid only under certain prescribed conditions. When we don't know what the conditions are, I think it's almost ridiculous to talk in terms of half-life of these materials—for instance, DDT. Some people say it has a half-life of seven years or ten years or more.

Allen Agnew:

I'm certainly glad to have somebody question some of these numbers that we keep putting in the books, in the guidelines, in the rules and regulations. You know, I am a geologist but I run into very interesting textbooks on hydrology. One is by Ray Kazmann at Louisiana State University, called "Modern Hydrology." What he did was puncture many of our hydrologic sacred cows, and he used the term "dirty data." He said that our reports are full of dirty data—data that have been collected over the years in various ways and we have come to accept them as the Bible. Well, about a year ago the U.S.G.S. went through its old data and gathered information on heavy metals. Well, they put a disclaimer in the very front of the report in the very first paragraph. But how many people read that disclaimer, or how many people would pay any attention to it? They would look down through the tables and see the statistics of these heavy metal concentrations, then they would take off from that point as they would begin to gather their new data on mercury, or whatever else they happen to be working on. I think we need to be particularly careful of this sort of thing. Well, once I've said this, I realize that we're talking to ourselves, and this group here probably doesn't need to be warned of this problem. We should make sure that the people who will use the information that we put out realize the bounds that should be on it.

Dick Rhindress:

Off the subject—but not quite. In Pennsylvania we have had several incidents where drugs have had to be disposed of in large quantities. The ships' stores for the whole east coast for the Navy are adjacent to Harrisburg, and they have tremendous amounts of drugs which go out of date. What to do with them? Some of them cannot be burned; some of them are not soluble so they cannot be run through a sewage treatment plant; others will wipe out a treatment plant even in small doses. What do you do with them? So far, we've put some in a landfill, but only the ones that we have judiciously felt would be decomposed in a landfill environment. Some of the others we're still up in the air about. They're sitting over there in the Naval Depot waiting for somebody to say what to do with them. The Navy itself is also working on what to do with them. I haven't seen any data on this problem. We've had railroad cars and trucks overturned with drugs in them; we had a fire in a major railway yard which destroyed, or partially destroyed, some drug shipments; and we had to get rid of this stuff. And this stuff is probably as bad, in its own way, as petroleum or pesticides. What do you do with it?

Allen Agnew:

Thank you. This leads into my question. I believe in your paper you were talking about the cost of abatement, and you said something like—the cost of the abatement wells and other costs make the cost of prevention worth more than the cost of clean-up. So what we need to do is push for preventive programs. My question is—what kind of preventive programs, and how do we do it?

John Matis, Maryland Department of Water Resources, Annapolis, Maryland:

I've participated in a number of these interagency groups where we try to decide what we would do in an emergency situation with hazardous wastes—if you want to call them hazardous wastes. That term covers a multitude of sins—drugs, wastes from hospitals, pesticides, petroleum, etc. You really need to develop ahead of time, some type of emergency procedure for getting rid of these things. The trend that I've seen is toward high-temperature incineration as the answer to everything. However, as we know, many of these waste products have heavy metals which are not going to high-temperature incinerate, so you're left with the heavy metals.

Perhaps legislation to reduce supplies is necessary to permit transport of the unused quantities out of the State, out of the area. This is another approach; it's been suggested that you have legislation requiring yearly inventories of whatever they had not used, whether it be drugs or pesticides or some other hazardous waste product, and that their return to the manufacturer be permitted.

Now as far as your specific problem of getting rid of these drugs, I would say that return to the manufacturer would be one way of doing it. This is one way we've gotten rid of pesticides in Maryland—large quantities of pesticides, I might add, which have been condemned or made illegal for usage, such as DDT.

In States like Massachusetts, they went on a massive collection program and collected tons and tons and tons of DDT and other things, and they really don't know what to do with them now. This is simply because they didn't have some type of procedure developed at the time to handle this problem. I think you really won't know until you actually encounter the situation. Is this an evasive answer?

Harry LeGrand:

The question arises as to whether we should have a special burial ground for these exotic wastes that don't attenuate in the ground as easily as would regular sewage. I'm thinking of pesticides and many exotic chemicals. We know that many of our sanitary landfills are not ideally located, as far as the best hydrogeologic criteria are concerned, and we know that, if we have to, we could upgrade a site location in each county to the point that we could have a separate spot, you might say, to bury this particular refuge. Would this be suitable?

Doug Olesen, Battelle-Northwest, Richland, Washington:

Battelle's prime contract is with the Atomic Energy Commission at Hanford, and the AEC in particular is faced with the problem of the long-term retention of hazardous materials. Their philosophy to date has been simple containment, and they're working on a number of long-term disposal techniques. But they definitely have adopted a philosophy of national repositories, Hanford being one, and there are a number of others. The Kansas Salt Mines are also under consideration—also under attack—but this is one obvious alternative.

Battelle-Northwest is also looking at national disposal sites, and we're also working in the area of hazardous materials and information systems for EPA. Our work is more or less cataloging what is known on hazardous materials and producing an information-system format. EPA then is working toward having some sort of a system on line so that when you get a major hazardous spill in a particular area where the man on the scene is not particularly knowledgeable about what is spilled or what should be done about it, hopefully this system will be such that a simple telephone call will hook him into a computer system and he'll be able to get all of the specific facts, including a contingency plan and where the particular materials or equipment are located for handling the type of spill that he has. No, it isn't liquid only. (Note: this is in answer to "Liquid only?" from unknown in audience.) EPA's emphasis obviously has been in the water area, because they started as FWQA, and Battelle's work has been with EPA's Water Quality Office so far.

Jay Lehr:

I'd like to comment on Harry LeGrand's comment. Sometime ago, I espoused the idea that somebody could make money by building treatment plants that could handle industrial wastes, and if the government got tough enough on the industry, the latter would be in a position where they would have to ship their waste to some central treatment plant that is really equipped to take care of it. I think we really can take care of virtually any normal industrial waste. It's just a matter of economics. Even your sulphur liquors in the paper industry can be taken care of, but it is an economic problem.

Speaker not identified:

The way we're trying to do it now, in a shotgun approach, is ridiculous. We must look at it on a national level. I think it can be done if we can mobilize everybody.

John Matis:

A couple of comments on things that have been said. Virginia and Maryland jointly are looking at the possibility of high-temperature incineration for handling of hazardous waste—anything that can be incinerated. This is an ongoing project. As far as Lehr's remark about industrial people making money out of this, it is happening in Baltimore at the present time. Rob Tyler, Inc. is an example—their slogan is "We Never Refuse Refuse." They have a site which is 80 acres or so where probably the most toxic materials you can ever imagine have been deposited. Well, this is really not acceptable, and they know this, so they are trying to find other ways. The State has forced some of the industries which will bring in cyanide waste, for example, to take it to areas where they could reprocess the cyanide.

Secondly, waste oil is a big problem in Maryland, as it is everywhere—45 million gallons a year, or something like this, is not accounted for. We don't allow these in landfills for the obvious contamination and hazard contamination problems. This outfit, Rob Tyler, Inc., has built a high-temperature incineration facility in Baltimore and they can make money with it. They take these things and burn them up. Of course, they comply with the air pollution controls, but it is still a profitable thing at the present time. If you have the facility, or if you have the capital to build one of these things, you can make money. Now, I think this will probably be a short-term affair because

States and many of the industries realize that they do need the regional approach—they do need these facilities to handle all this multitude of sins called hazardous wastes. So you will see more of these facilities being operated and, as I say, Virginia and Maryland are talking about a joint effort at the present time.

Dick Rhindress:

On the subject of hazardous wastes, we find they really fall into two categories: one category is typified by the instance I gave before, the Navy depot that has tremendous quantities of drugs, those we can at least store for awhile until we come up with a plan. When somebody brings in a truck of X chemical from Ohio on its way to New Jersey, and it splits in half on the Turnpike and we have to shovel it up in an hour or two and know what to do with it so that we can get the Turnpike open again, that's a whole different ball of wax. Some of these chemicals have been such that we couldn't send men in to handle them because we had to have special uniforms and some wastes were absorbable through the skin. One was a solid, but it was so soluble in water that we had to get it out of there almost immediately because it was raining about ten miles west of it on the pike and moving toward us. These are the types of things that are real problems.

You have to get it out of there, protect it, and what do you do with it? We, sort of jokingly sometimes say, "Aha, we got it out of here, we got it to New Jersey" or "back into Ohio." But this is begging the question. You know, you can't always just send it back to the manufacturer. That's begging the question too, because if the manufacturer is in your State, you're going to just relocate the problem. If he's out of State, you're just passing the problem on to somebody else. This plan that EPA and Battelle are working on, of having a national clearing house on what to do with these chemicals is fantastic. This is what we must have, and we must have instant access to it, for the emergency type situation which happens all too often at midnight—this is when they always happen; they never happen at 9:00 o'clock Monday morning when you can work on them.

Mike Bell:

Some things to be considered in developing a regional approach are the economics and the conditions that are necessary for transporting a hazardous waste. How far does it have to go and what precautions need to be taken? We ran into this.

Elmer Jones:

I would like to return to the problem of pesticides in well water, and I use this term in place of ground water because in every case I have looked at carefully, I'm personally convinced the pesticides entered the well above the water table. Any rain that falls today is going to contain some DDT. Most of the water samples that we've analyzed have been below concentrations reported for rain water. The pesticides—chlorinated hydrocarbons—are almost totally insoluble and very tightly bound to particulate matter. Our findings are that they are almost invariably associated with gross bacterial contamination and variable turbidity with rainfall. Neither of these characteristics are characteristics of good well construction or good quality ground water. And, as John Matis pointed out in his talk, the initial approach with the people who have this problem is tremendously important.

There is one well in Maryland that had a $100,000 lawsuit over it because of the home being treated for termites with Chlordane. We were terribly afraid we'd end up with this in court because we had monitored this well for about three years. It was cased with open-jointed clay-tile casing (the lowest point in the pit adjacent to the house was the top of the clay tile casing). The pit received drainage from a road and off the house. When the Health Department was first contacted about an abnormal taste in the water, I feel this problem would have been eliminated almost immediately if the undesirable nature of this well construction and location had been pointed out to them, and they had been urged to have a properly protected well constructed. As it was, awaiting litigation, they were told by the lawyers to do nothing to the well, so they ended up carrying water into the house for four years while awaiting a solution in court.

But the earth is a good filter and the question with regard to sanitary protection of wells is "At what point does the natural filtering ability of the earth begin?" This is something I was concerned about for quite some time—having dug a lot of fishing worms in my life—that pesticides were always found in the upper soil layers and it was said they never moved down—and yet we know that soil insects go much deeper than this. As it turns out, in the deeper soil profile some of the pesticides undergo much more rapid degradation by action of organisms. Apparently this degradation is sufficiently rapid so that samples taken at the level of some of the major insects show that the degradation rate is as fast as the pesticides move down to this level.

Allen Agnew:

Elmer, I think that you've put the finger on a subject that the N.W.W.A. is particularly happy to see emphasized—that is, improved construction of wells. This is one of the cardinal points that N.W.W.A. has stood for and, in working with the State associations of water well drillers, this is one of the points they've attempted to get across. You recognize that the State associations unfortunately don't represent all the drillers in the State, or all the well diggers. So we've got a big job to do back home and I think that the N.W.W.A. will be pretty happy to see the kind of emphasis that we are putting on it at this session.

Now, we're approaching our close—you remember that when Lady Godiva came roaring down the street naked on her horse, she said, "I approach my clothes." She spelled it differently from the way I spelled it just now. It is 9:30—the time that I had hoped would be our close here, but we still have some people who haven't talked and I'm sure that you've got some things to say that are so pregnant that you just can't stand not to say them.

Dick Pearl, Colorado State Geological Survey, Denver, Colorado:

I was just wondering if any of you people from the East have had any contact with any research being done on degradation of DDT in the soil by any means? The reason I ask is that research is being carried on up at Colorado State University and, if my memory serves me right, they're finding that cow manure is a very useful agent in this. It destroys DDT very rapidly in the soil, and I was wondering if there's anything else that maybe you've found that does the job.

Max Lewallen:

Elmer Jones has already provided you with some of that information. There is quite a bit of that work being done presently. One other thing I might mention—you referred to cow manure—I believe alfalfa meal has been in the literature also as one of the things that aid in degrading some of these materials. But, when we talk of the degradation of these materials, it's a similar situation to the half-life that we referred to awhile ago. You're talking about very specific conditions on the degradation of any of them which can be either a fast or slow degradation. For instance, I remember reading over a report where in one particular instance DDT was being used in a tropical climate for the spraying of mud huts and the problem there was too short lived, under those conditions.

Verne Farmer:

Is DDT not all as bad as the newspapers say it is?

Elmer Jones:

I think this is a yes-or-no type answer. DDT at high pH can be very rapidly broken down by hydrolysis. This is a condition you will not find in nature. A large number of very common anaerobic organisms, *E. coli* being one of them, can break down DDT. The problem with DDT in the environment has been largely with what you might call the "accidental fraction." The pp DDT, and I'm not going to attempt to define this because I am not an organic chemist, is the desirable pesticide. The op DDT is the accidental portion and depending upon the manufacture and the date of manufacture, this will run from 5 to 20% of the active agent. Unfortunately, in the environment, this is so similar to certain female hormones that it (not the pp but the op) has had an effect on maturity and sexual activity of wild life. The thing that has been a real bugaboo, and I think that perhaps last year we may have seen a pesticide backlash (now this is a personal opinion, not an official Department of Agriculture policy statement), because of the publicity on DDT, its persistence, a coming ban, and a lack of a good substitute in some cases—perhaps some farmers have tried to put on enough to last five or six years.

It is impossible to describe normal conditions but perhaps normally 50% of the DDT applied to an area will be lost to the atmosphere within 48 to 72 hours. As you know, they talk about finding it in the Arctic for seals and in places that they are sure no pesticides were ever used. The English have done much more work on pesticides in the atmosphere than we have. Their findings are that in the atmosphere, its average life, or half-life, is long enough for it to go around the world about three times. I talked about it in rain water because I'm concerned with pesticides in water, but these Englishmen, Adkins and Eggleston, estimate that about eight and a half times as much is removed from the atmosphere by deposition as by rainfall. So you have a continual replenishment over the earth's surface of DDT and, until you know this rate of replenishment on the surface, you cannot accurately calculate the survival of this in the soil. I think this has been a complicating factor, but in the last two years there has been more and more information on the degradation of these, and the anaerobic environment which we don't find in our agricultural soils is much more conducive to such degradation.

A good example of this is when my project on pesticides was started by Robert Egan of the Maryland State Health Department, hetrachloric peroxide was frequently found in water supplies in the Hagerstown Valley. When this was banned from use on alfalfa, even though it persists in the soil for a long period of time, our detecting it in water supplies essentially cleared up within the year. The question is not so much the persistence, but the damage that it can do in its lifetime. And this is because of its mobility, especially with regard to water; you cannot make DDT stay in pure water. It will be carried out by a process known as codistillation. The DDT has a very low volatility, but it will be attached to the water molecules going off.

John Matis:

I have a question for Lewallen or Elmer Jones. If DDT goes around the world three times before it is finally degraded and it comes down in the rain water, it would seem to have some kind of impact on photosynthesis in general, whether it be in the oceans or in lakes or standing water bodies. Is this true, or not?

Stan Ursic, U. S. Forest Service, Oxford, Mississippi:

We have had some people working on the hard pesticides as applied to forest land, and they have found that the persistence is very low, as measured in surface water from measured water sheds. They don't detect the hard pesticides after a matter of a few days, due to the high biotic activity, especially within the forest floor.

If I may continue, I have a question and a comment. It seems that most people at this Symposium are geologists, hydrologists, and engineers. The one paper we didn't hear today was by a research chemist. For a neophyte getting into the field, I'd like to hear comments on your experiences about what to do to get reliable chemical analyses. I realize that you can go out and hire a Ph.D. chemist, but perhaps this isn't always the best solution, unless you're a big outfit like ARS. What are your experiences? Do you go to State agencies for your analyses? Do you go to private firms?

My other comment is, I was a little disappointed in not hearing anything at all this evening about industrial wastes, and this seems to be a problem that is certainly as important as gasoline spills. For example, I know that International Paper Company, between 1970 and 1974, will plan to spend $100 million on pollution control alone. This is just one paper company—it happens to be a big one—but there are others, quite a few. Are we neglecting this area? Are we skirting this area for any particular reason?

John Matis:

Industrial wastes include a large number of things, very complicated wastes. Those of us who are interested in petroleum know that we have waste products. I'm familiar with waste oil. This is an industrial waste, and it is a very severe problem. I do know that many of the petroleum companies, at least in the Baltimore area, are spending very large amounts of money on pollution control measures. There obviously have been occurrences in the past which have created ground-water problems—these are really what we're concerned with. It's well documented that many of these waste lagoons have caused phenolic concentrations in the ground water beneath. When you say "industrial wastes" exactly what are you thinking of? It can include many, many things.

Stan Ursic:

Well, I was thinking of the whole gamut—the paper industry, the people who make these hard pesticides that we're talking about. You are all familiar with the Mississippi River kill, and this sort of thing. I'm speaking of industrial wastes in general.

John Matis:

One point which has become very obvious to us in Maryland; when you turn off all the spigots and all the discharge points into the surface water, the liquid waste has to go somewhere. I think Dr. Zanoni made this point—every waste has to go somewhere. And at the present time, with the very restrictive surface water laws, most of it is no longer being transported in water; it is going on the ground, and this is really our concern, whether it is pesticides, or washings from pesticide formulator plants, or from petroleum plants. It's going on the ground. This is indeed a problem and, as far as I know, in the northeast corridor from Washington up to Boston, with which I am familiar, this problem has not been evaluated. It includes chromium, steel plants, paint, and all kinds of chemical works. It has not been evaluated; people know it exists, and it could very well be the most severe problem that we're facing in ground water.

Max Lewallen:

I might contribute to his query concerning the analysis of these materials. I frankly know of no easy route to analysis of pesticides. If we're talking about controlled conditions, controlled experiments, known quantities, known pesticides being used, it is a much easier problem than say, if we start with a completely unknown sample. As you might well know, we've had analytical problems; a lot of others in the pesticide business with whom I have talked have analytical problems also. There are unresolved points. A lot of times in pesticide analysis if we stick with common compounds and known compounds, it eliminates troubles quite a bit. Others might want to make some comment with regard to pesticide analysis.

Doug Olesen:

We had a similar problem with Acrolein in a study that we were doing. The first year's work was based on analytical techniques that were supposedly acceptable and, after a full season of sampling, we discovered that it was a field problem. We discovered that the actual analytical techniques were not successful and we had to do a fair amount of basic research and go through and develop a completely new technique for Acrolein. I think a lot of people face the same problem. There's nothing to draw on; you just have to go it on your own until you can develop something that is satisfactory. We did document this and it is available now for other people, but many pesticides you run up against are likely to force you to go through that same procedure.

Stan Ursic:

Thank you. I was also thinking of just the routine analysis of the common cations and anions as well, rather than some of the more sophisticated or exotic chemicals.

Allen Agnew:

Mr. Ursic, it seems to me that EPA just recently reissued the second edition of analytical methods, or techniques—that big, spiral-bound manual that FWPCA put out 3 or 4 years ago, which contains standard analytical methods and apparently a re-evaluation of these methods. EPA has been doing some soul-searching too, in the last 3 or 4 years on methodology, both at the Evansville Station and the Wheeling Station that I know of, on the Ohio River. And the U. S. Geological Survey, of course, has Hem's Water-Supply Paper on Analytical Methods. So there are two major reference works, and I am sure that there are others; however, you still have the problem of the bench chemist—getting reproducibility of results, and the fact that some of them feel more at home with a certain analytical method than with others. So you really have to identify the methodology and the lab that's running the analyses, as you use the information in your report.

John Matis:

I'd like to make a few comments on analyzing petroleum. With the gas chromatograph (I really didn't go into this in my presentation), you can analyze things in terms of the light fraction or a heavy fraction. In other words, something which falls in the range of a C-4, C-6, C-8 compound and something which is up around a C-12 compound. This does not identify the specific product. In other words, if you have an unknown petroleum contaminant in water, you cannot identify it in minute quantities now. If you don't know what it is (in other words, it might be a kerosene, gasoline, or fuel oil), you are stuck because the kerosene, gasoline and this No. 2 diesel fuel (which is really a kerosene) fall within the same range of identification by your gas chromatograph techniques. This is a real problem. The infrared spectrophotometer technique requires that you isolate this stuff with some type of organic solvent—chloroform has been used. A number of papers have been written on this, many of them unpublished, by this Kankawi group in Europe, but more recently by Crider with Standard Oil of California.

And you need a large volume of sample to concentrate, let's say 0.1 ml; I don't know if this came across in my talk. Now this assumes that nothing volatilizes in the meantime, and that you can keep the solution; their technique has been to get so many milliliters of chloroform or organic solvent, collect the water in the same bottle, and then draw out the solvent and analyze this concentrate, boil it, reconcentrate the material and then analyze it with the gas chromatograph infrared spectrophotometer.

There is a real problem, though, with identification and sampling. Now, we have been faced with the situation where we really never did resolve a number of incidents where we suspected it was kerosene or gasoline, because of this problem. As a result, very little legal action could be taken. I don't know if this clarifies our sampling techniques. Dale, you may want to talk about your experience in California.

Dale Wilder:

A couple of things have come up that I did want to talk about. One deals with sampling techniques—we found that, among other things, we had a very difficult time in estimating how much gasoline was in the well, and also which wells had the taste and odor of gasoline. Part of the problem is that when you're out in the field sampling 70 wells, it is a difficult procedure cleaning up your M-scope, or whatever you're using, to measure the levels with. Of course, much of this is just developing a standard practice of carrying detergents or whatever it is that will cut the gasoline and get rid of the odor.

The other thing, mentioned earlier, is the cost of preventive measures in comparison to the cost of the remedial action. I mentioned in answer to one of the questions that was asked that $700,000 had been spent by WOGA. This is not an overly large amount of money, as far as the petroleum industry is concerned, except that this is just a small part of the total clean-up that was involved. There were several agencies who went ahead on their own and did what they thought they could. Also the Department of Water and Power has done this to insure that their wells will remain free from gasoline. In addition to this, WOGA requested that we do some monitoring for them. But, the point is that in the past it has tended to be quite an economic consideration, but now it has become more economical to make sure that it doesn't get spilled in the first place. It was a little hard to justify going ahead and spending this money. I think that we need to put forth a real effort, as an organized group, to make sure that economics isn't the only consideration that companies look at when they are deciding about preventive maintenance.

Doug Olesen:

The business of tying economics to environmental considerations has just become official policy because of the recent Calvert Cliff decision—that was a lawsuit by interveners against the Calvert Cliff nuclear plant, where the AEC and other government agencies actually lost the case and were accused of absolute neglect in terms of the National Environmental Policy Act. One of the things that came out of this decision is that all environmental impact statements now—in essentially all industry—will have to have an economic consideration tied to the environmental impact statement, so that it will actually be an economic trade-off for various alternative actions that industry can pursue.

Elmer Jones:

I want to add my comments on the analytical services. This is a problem because of the expense of the equipment involved. I think there is a real need for more environmental monitoring. If we are going to protect our environment, we need to know what is going on. Because of the shortage of qualified personnel and the cost of the exotic equipment needed to test in the parts per billion and parts per trillion range, consideration should be given to regional analytical services where you can have a well-equipped and well-staffed lab with people of high caliber to train the next generation of analytical chemists for environmental monitoring.

Mike Bell:

I apologize because the time is running late, but I do have an important question that I think needs consideration, going back to contamination of ground water by gasoline. What happens when the gasoline gets into the ground? How far can we expect it to go; what conditions in the ground determine how far it goes; what happens once it is there as far as its movement; does it degrade; it is just there; what can we expect once it is in the ground?

Dale Wilder:

In our experience, it appeared that the gasoline was very mobile. However, because of the residual that was left behind, it tended to dissipate itself. That is, a certain percentage of it would be left behind in the pores that it traveled through, and so the distance it would travel would depend very much on the volume that was originally present. As far as what happens to it after it is in residual form, this is part of the problem that we're having. It appears that certain organisms can degrade it. Whether it degrades on its own, I don't know.

John Matis:

In the case near Los Angeles which I explained in my talk, the gasoline had been sitting there for at least three years, or maybe for as much as ten years. It did not move out of the area. It sat there as a pocket of gasoline and did not degrade appreciably. In another case where I personally examined the well—it was a small area perhaps one acre in size—the gasoline had been sitting there for at least six years, and the people's wells were still contaminated with strong odor and strong taste. So there was a definite problem. The gasoline did not move, as you might have imagined and as Dale Wilder has indicated; the movement was limited. I don't know why this is true. I think the people in Europe are working on that particular problem.

Doug Olesen:

We face a similar problem with radioactive waste, where it doesn't move with the water. Some things move at something like 1/1,000th the rate of the water movement because of the soil-waste interaction (adsorption, precipitation—there are a lot of things going on). In addition to biological degradation, we are dealing with an organic material. But it always comes back to the fact that the key to the answer has to be that you have to be able to satisfactorily describe a velocity pattern and the flow of the water system. If you can do that, then you can deal with the soil-waste reaction that is going on and try to make some prediction that the contaminant itself will move at some fraction of the speed of the water. It's always going to go where the water goes, but it may not go as fast, and that is the crux of the matter; but the key is knowing where the water goes.

On one other observation, it seems everybody is talking about contingency plans for dealing with emergencies of contamination or pollution of ground water. This could be an excellent recommendation from our group—a contingency plan to deal with emergencies, be it in Washington or North Carolina or California or Maryland or wherever.

Harry LeGrand:

Well, we have contingency plans when it comes to a snowfall hazard, and we have piles of salt and sand on the road. I can visualize piles of clay, or something like that to help mop up some exotic chemical, but I hope we don't have cow manure piles to take care of the pesticides, as someone suggested earlier.

Allen Agnew:

I move we adjourn with that one. I want to thank everyone for contributing your thoughts and pointing out the failings and the fallacies that we are living with. We mentioned earlier the term "corporate responsibility." I would like to remind us that we also need to have individual "citizen responsibility"—for example, our own municipal waste-treatment plants, when we taxpayers won't vote the bond issues necessary to clean up our wastes. We are some of the worst polluters that exist around here. Gentlemen, let's all put the wheel to the shoulder — or some other mixed metaphor — and get on with the job. Thank you.

Ground-Water Pollution Potential of a Landfill Above the Water Table[a]

by Michael A. Apgar[b] and Donald Langmuir[c]

ABSTRACT

A study of the character and movement of landfill leachate through unsaturated soil was begun in 1967 at the State College (Pennsylvania) Regional Sanitary Landfill which has operated since 1962 employing the trench method of waste disposal. The landfill occupies a gently sloping underdrained valley with a water table more than 200 feet below land surface. Precipitation averages about 37 inches as rain per year. Residual sandy-clay to sandy-loam soils range from a few feet to greater than 70 feet in thickness on a sandy dolomite bedrock. Soil moisture samples were extracted at different depths from beneath two of the refuse cells using suction lysimeters. Water samples were also bailed from these cells and pumped from a water table well beneath the landfill. Monthly or less frequent analyses performed on water samples included Eh, pH, temperature, specific conductance, BOD, Cl, SO_4, total alkalinity, NH_3, NO_2, NO_3, PO_4, Ca, Mg, Na, K, and total Fe. Soil samples from beneath the refuse were subjected to particle size and x-ray analysis, and chemical analysis of soil pH, soluble salt content, exchangeable Ca, Mg, Na, and K, cation exchange capacity, and extractable P content.

The study showed that the quality and quantity of leachate beneath a landfill varies considerably with the topographic setting of landfill trenches or cells. Leachates 2 feet under an upslope cell which received only direct precipitation, had the following maximum values 3-13 months after refuse burial: specific conductance 8445 µmhos, Cl 1890 mg/l, BOD 3300 mg/l, NH_3-N 540 mg/l, and total Fe 225 mg/l. Upon reaching a depth of 14.5 feet after about 2½ years or more, maximum values of these species in the leachate had been reduced by 83%, 80%, $>99\%$, $>99\%$, and 98% respectively. In contrast, more water, including precontaminated surface and subsurface runoff from adjacent upslope cells, infiltrated a downslope cell, saturating the refuse. Even after moving downward in the soil to a depth of 36 feet in 7 years, the leachate beneath this cell had a conductance of 6600 µmhos, 600 mg/l Cl, over 9000 mg/l BOD, 40 mg/l NH_3-N, and 100 mg/l total Fe. A practically continuous depletion of inorganic species in the refuse as indicated by the quality of leachate from both cells has occurred with time. However, concentrations of BOD and redox sensitive species such as Fe and NH_3 in the leachate have fluctuated in response to changes in the moisture content and temperature of the refuse.

Leachate beneath instrumented cells is moving downward in the subsoil at the rate of 6-11 ft/yr. Observed mechanisms of leachate renovation during this downward percolation, along with supporting evidence for each listed parenthetically, include: dilution and dispersion (decrease in Cl with depth); oxidation (Eh and pH measurements, decrease in BOD and Fe with depth); chemical precipitation (decrease in soil extractable P after leachate percolation); cation exchange (increase in percent base saturation of clays affected by leachate, and depletion of NH_3 under reducing conditions—bacterial growth may also retard or remove NH_3); and anion exchange (decrease in SO_4 with depth). Removal of bacteria, suspended ferric oxyhydroxides and other particulates by soil filtration undoubtedly also occurs. Although renovation takes place, it is incapable of preventing highly contaminated leachate from moving to depths of 50 feet or more in soils beneath downslope cells. Ground-water contamination has occurred, probably by leachate channelled down fractures in locally shallow bedrock, or by leachate-contaminated runoff from heavy storms which has entered sinkholes or infiltrated along the valley bottom. The study shows that improper design of landfills emplaced above the water table in relatively permeable soils and bedrock such as are found in many carbonate-rock terranes, can result in serious ground-water pollution.

INTRODUCTION

Ninety percent of all municipal solid wastes generated in the United States are disposed of on land. About half this total goes into landfills, the rest to open dumps (Hershaft, 1969). In the near future as public outcry against open dumps becomes more universal, most of such disposal will also give way to landfilling. Thus landfilling will be the prevalent method of solid waste disposal in this country for many years to come.

A sanitary landfill is defined as an engineering method of land waste disposal which creates "no nuisances or hazards to public health or safety" (American Society of Civil Engineers, 1959). However, in practice any operation in which refuse is compacted and covered with soil on at least a daily basis is considered a sanitary landfill. Landfills are indeed more sanitary than open dumps in terms of controlling odor, fires, and vermin, and in permitting site reuse. However, leachate produced in the decomposition of refuse in dumps or landfills may pollute surface and ground water. The nature of such pollution will depend on whether the decomposition process takes place in the presence of atmospheric oxygen or soil air (aerobic) or in the absence of oxygen (anaerobic). Aerobic decay produces stable end products such as CO_2, NO_3, SO_4, H_2O, and a relatively inert residue. Anaerobic decay produces CO_2, methane, ammonia, hydrogen gas, alcohols and organic acids, and other partially oxidized organic species which exert a high BOD (biochemical oxygen demand). Metals such as iron and manganese are mobilized and may be concentrated in such reducing environments.

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Refuse cells usually become predominantly anaerobic shortly after emplacement (Merz and Stone, 1962). In general, conditions are relatively aerobic near the surface of a refuse cell and become increasingly anaerobic towards the bottom. However, within refuse cells unsaturated by water, traces of oxygen are often present, so that zones and pockets of anaerobic and aerobic decay will exist side by side at any depth (Merz and Stone, 1966).

Leachate quality is influenced by the composition and amount of refuse, its sorting and degree of compaction, the amount of water in contact with it, and the temperature. Refuse constituents which affect leachate quality include biodegradable organic matter (chiefly vegetable and animal wastes), soluble inorganic materials, and redox-sensitive substances such as most metals. The composition of a typical municipal refuse is given in Table 1. In general, the thicker the refuse, the more polluted the leachate issuing from it (Quasim and Burchinal, 1970). The manner of sorting of the refuse is important insofar as reactive materials such as the biodegradable organics in garbage may be isolated by relatively inert materials such as paper. Paper also absorbs and holds water which would otherwise promote the decomposition of other organic materials.

Table 1. Sample Municipal Refuse Composition – U. S. East Coast (after Kaiser, 1967)

Physical	*Weight Percent*	*Rough Chemical*	*Weight Percent*
Cardboard	7	Moisture	28.0
Newspaper	14	Carbon	25.0
Miscellaneous paper	25	Hydrogen	3.3
Plastic film	2	Oxygen	21.1
Leather, molded plastics, rubber	2	Nitrogen	0.5
		Sulfur	0.1
Garbage	12	Glass, ceramics, etc.	9.3
Grass and dirt	10	Metals	7.2
Textiles	3	Ash, other inerts	5.5
Wood	7		
Glass, ceramics, stones	10		100.0
Metallics	8		
	100		

Water cannot readily enter refuse which has been highly compacted. Such refuse settles less after burial and is less susceptible to channelling and to changes in permeability than less dense material. Compaction also reduces the rate of atmospheric O_2 diffusion into the cell and thus favors anaerobic decay of the refuse.

Water content determines the rate of refuse decomposition, and whether the process is predominantly aerobic or anaerobic. Dobson (1964) reported that the maximum oxygen uptake by microbial decomposition occurred in refuse with 40-80% moisture content. The maximum decomposition rate was observed at a moisture content of 60%.

Water content of the refuse is a function of its initial moisture content, water produced in decomposition reactions, ground water which may enter the refuse, infiltration of precipitation and runoff through soil cover, and lateral flow in the soil. The amount of recharge to the refuse cell is determined by the permeability of the cover material and the topographic setting, among other factors. Vegetation, or leaf mulch cover disposed of on the site will prevent rapid storm runoff, and thus may increase infiltration to the buried refuse. Vegetation, however, will also reduce the water content of the refuse through transpiration.

Most water which infiltrates a refuse cell will not appear as leachate until all the refuse layers have reached field capacity (Remson, Fungaroli, and Lawrence, 1968). However, some leachate is produced immediately after refuse burial by compaction of initially wet refuse or channelling of water through the refuse (Lane, 1969).

Reduction in the permeability of the cell floor may cause water to pond in refuse buried in unsaturated soils. Such permeability losses result from compaction and smearing of the soil by excavation and landfilling equipment, from precipitation of gelatinous ferric oxyhydroxides, or formation of an organic slime on the trench floor (McGauhey et al., 1966; Lane, 1969).

Temperature exerts an influence on leachate quality by controlling the rate of bacterial activity. Microorganisms are able to grow in refuse over the temperature range 5-55° C, but the largest number grow between 15-30° C (Dobson, 1964). A drop of 5°C results in a 10-20% decrease in the rate of bacterially - controlled oxidation (Camp, 1963). Thus, significantly less BOD is produced in a landfill in a temperate climate during winter and spring months than during the summer and fall (Langmuir, Apgar, and Parizek, 1971).

Burial of refuse in direct or intermittent contact with the zone of saturation has repeatedly been shown to cause serious contamination of ground water. Unfortunately, natural depressions and excavations which intercept the water table are frequently employed as waste disposal sites. Well documented cases of ground-water pollution resulting from such disposal have been reported in New York (Carpenter and Setter, 1940), California (California State Water Pollution Control Board, 1954), South Dakota (Andersen and Dornbush, 1968), and Illinois (Hughes et al., 1969). Saturation of the refuse by ground water not only permits the ready solution of inorganic material but also favors exclusively anaerobic decomposition of the organic wastes present with the formation of reduced and highly undesirable organic and inorganic substances.

In contrast, reported instances of ground-water pollution from landfills situated above the water table are virtually nonexistent. Thus, until recently it has been widely assumed that a few feet separation of refuse from underlying ground water is sufficient to prevent water quality problems (California State Water Pollution Control Board, 1954; Andersen and Dornbush, 1968; New York State Department of Health, 1969). This may be true in semiarid climates where significant amounts of leachate are seldom produced above the water table. However, landfills located in humid environments can be expected to produce leachate which may percolate to the water table without sufficient renovation to avoid ground-water pollution (Emrich and Landon, 1969).

Ground water in carbonate terranes is particularly vulnerable to pollution by landfill leachates. Carbonate rocks may weather to produce residual soils the thickness of which depends on the abundance of noncarbonate minerals in the parent rock and the extent of subsequent erosion. When these soils are present above the water table, they might be expected to minimize ground-water pollution by dispersing and retarding leachate flow and facilitating its aerobic renovation. However, carbonate bedrock may be locally shallow or exposed and often has solution enlarged joints and fractures ranging to cavernous in size. Such bedrock provides direct avenues for movement of raw leachate to the ground water with little if any opportunity for improvement in leachate quality. Further, solution enlarged openings in carbonate bedrock can permit leachate-contaminated ground water to travel great distances rapidly and without filtration.

PURPOSES OF THIS STUDY

An investigation of the ground-water pollution potential of the State College Pennsylvania Regional Sanitary Landfill has been pursued since 1967 by the Pennsylvania State University in cooperation with the Pennsylvania Department of Environmental Resources (formerly the Pennsylvania Department of Health). Purposes of the study which will be considered in this report include:

1. Examination of the quantity and quality of leachate produced in a humid-temperate climate by a landfill in unsaturated soils.

2. Determination of the rate of stabilization of such a landfill as evident from changes in the quality of its leachates with time.

3. Study of changes in leachate quality with depth in underlying soils to identify the extent and principal mechanisms of natural leachate renovation.

4. Evaluation of the possible extent of ground-water pollution by landfill leachate at a site with a deep water table in a carbonate rock terrane.

The study was begun by R. R. Parizek and B. Lane. Results of the research for the period October 1967 to July 1968 have been summarized by Lane and Parizek (1968), Lane (1969), Emrich and Landon (1969), and Parizek and Lane (1970).

DESCRIPTION OF THE STUDY AREA

The State College Regional Sanitary Landfill is located 1.8 miles northwest of State College in Centre County, Pennsylvania (Figure 1). Also shown in the Figure are areas in the State directly underlain by carbonate rocks which as noted are uniquely vulnerable to ground-water pollution. The study area averages 37 inches of precipitation as rain per year, distributed with a slight excess during summer months. Of this 37 inches about 5 inches fall as snow, generally between the months of November and April. Mean monthly temperatures range from a low of −2° C in January to 22° C in July.

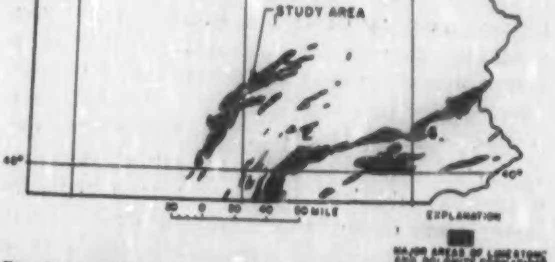

Fig. 1. Location of the State College Regional Sanitary Landfill (see also Figure 23), and major areas underlain by carbonate rocks in Pennsylvania.

The Landfill site, the southwestern half of which is shown in Figure 2, occupies 108 acres, or most of a small valley on an upland ridge in the center of a broad, carbonate valley called Nittany Valley. The bottom of the small valley is dry and underdrained and contains surface flows only a few times a year after the heaviest storms. Landfilling is done along the valley sides, the tops of which parallel the dry stream bed. The valley walls are about 60 feet high and slope 7-10° toward the stream channel.

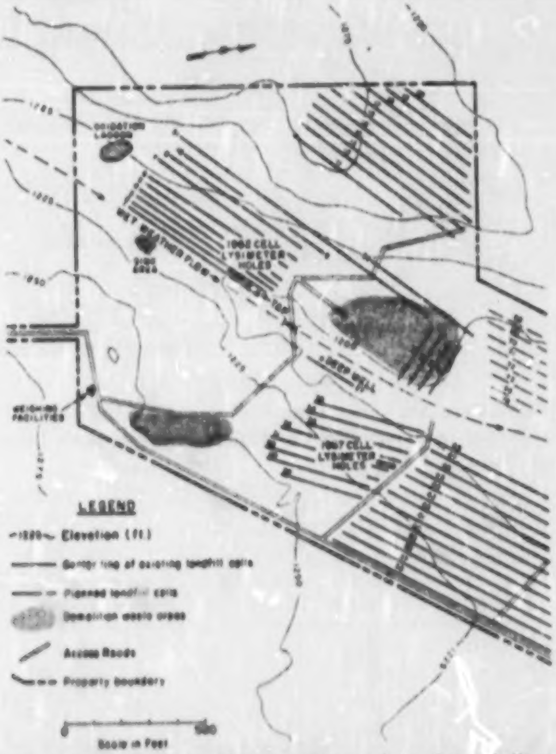

Fig. 2. Map of the southwest portion of the State College Regional Sanitary Landfill, showing locations of holes for the 1962 and 1967 lysimeter networks, the 1962 cell tap, and the deep well.

Ground water exists under water table conditions at a depth of about 200 feet in the bedrock beneath the dry stream valley. Bedrock is the Upper Sandy Member of the Gatesburg Formation of Cambrian age, an interbedded series of dolomites, sandy dolomites and quartzites. Residual soils developed on this unit range from 0 to greater than 70 feet in thickness. Although bedrock does not outcrop on the landfill property, it immediately underlies the buried refuse in some places.

Local soil textures range from sandy loam to loamy sand (Lane, 1969). However a typical soil profile is very heterogeneous and may in addition include lenses of sand or clay, large quartzite or dolomite boulders, and occasional unweathered ledges of quartzite or dolomite. These units control the rate and direction of soil moisture movement beneath the landfill. Sandy units allow rapid movement and channelling, while clayey lenses and rock ledges retard or deflect soil-water movement (Lane and Parizek, 1968).

Before 1962, the Borough of State College used the southern end of the present landfill tract as an open dump. In 1962, all exposed refuse was covered, and the site has subsequently operated as a sanitary landfill. Five townships surrounding State College have also disposed of their refuse at the landfill since January, 1967. In 1970 about 100 tons of refuse were brought to the site each day for burial.

The landfill is operated by the trench method (American Society of Civil Engineers, 1959). Individual refuse cells are about 30 feet wide, 12 to 16 feet deep, and range from 200 to 1200 feet in length. Inert, bulky material including demolition debris and tree stumps are dumped in separate areas of the landfill to conserve trench space. Refuse cells are covered with a final layer of compacted soil ranging from a few inches to 2 feet in thickness. Leaves gathered each fall are spread over the completed cells as mulch cover. Final restoration involves planting evergreen seedlings throughout the area, although natural grass and shrub vegetation predominate about 5 years after burial.

WATER AND SOIL SAMPLING METHODS

Water Sampling Methods

Soil moisture samples for this study were extracted by means of suction lysimeters from beneath landfill cells which had been emplaced in 1962 and 1967. The design and operation of suction lysimeters have been described in detail by Lane and Parizek (1968), and Parizek and Lane (1970). The cross section of a lysimeter is shown in Figure 3. The device, which can hold 1 liter of water, consists of a plastic cylinder 25 inches long and 2 inches in diameter, with a 2.5 inches long porous ceramic tip or cup. Soil moisture is drawn through the powdered quartz and the ceramic tip into the lysimeter by the application of a vacuum greater than the soil moisture tension through the pressure-vacuum tube. A sample is then forced to the surface for collection by exerting a gas pressure on the pressure-vacuum tube. As noted by Lane (1969) the pore diameter of the ceramic tip is approximately 1 micron or less. Thus, most colloidal-sized particles can enter the sampler; however, many particulates including bacteria and perhaps some BOD active substances are excluded from sampling.

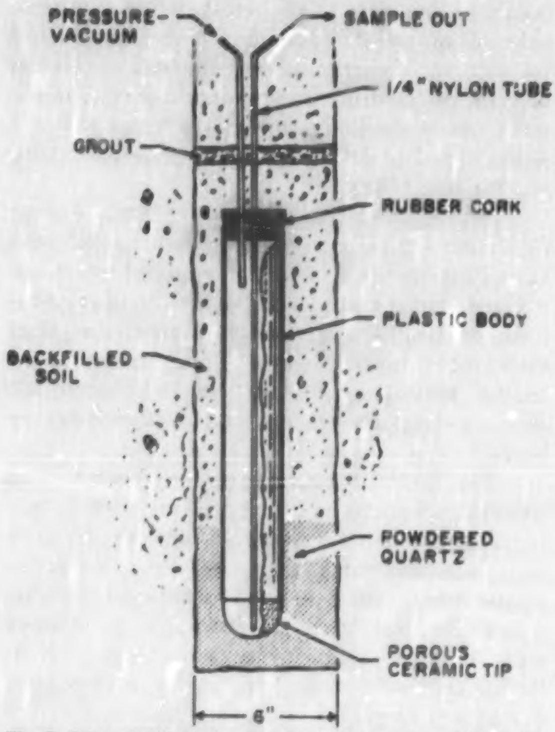
PRESSURE-VACUUM
SAMPLE OUT
1/4" NYLON TUBE
GROUT
RUBBER CORK
PLASTIC BODY
BACKFILLED SOIL
POWDERED QUARTZ
POROUS CERAMIC TIP
6"

Fig. 3. Cross section of a suction lysimeter, modified after Parizek and Lane (1970).

The 1967 cell lysimeter network and leachate collection facility were designed and installed by Lane and Parizek (1968) (see also Lane, 1969). A generalized plan and profiles of the installation are shown in Figures 4 and 5. Prior to emplacement of refuse a plastic liner of double thickness six-mil polyethylene was laid along the bottom and 6 feet up the sides of the trench to collect and conduct leachate towards the lysimeter network. A galvanized iron spreader pipe directly above the network received and distributed the leachate evenly into a gravel-filled trench from whence it filtered downward through the soil towards the sampling points. A cross section of the lysimeter sampling network beneath the 1967 cell is shown in Figure 5. Pelletized bentonite was placed at intervals between lysimeters during backfilling of each hole with native soil to prevent leachate channelling to the sampling points. Sampling tubes from the lysimeters were completed in a protective wooden housing set on a concrete foundation on the floor of the landfill trench (Figure 4). After the refuse had been emplaced to a depth of 10 feet in November 1967, access to the sampling tubes was accomplished by raising the hinged roof of the housing.

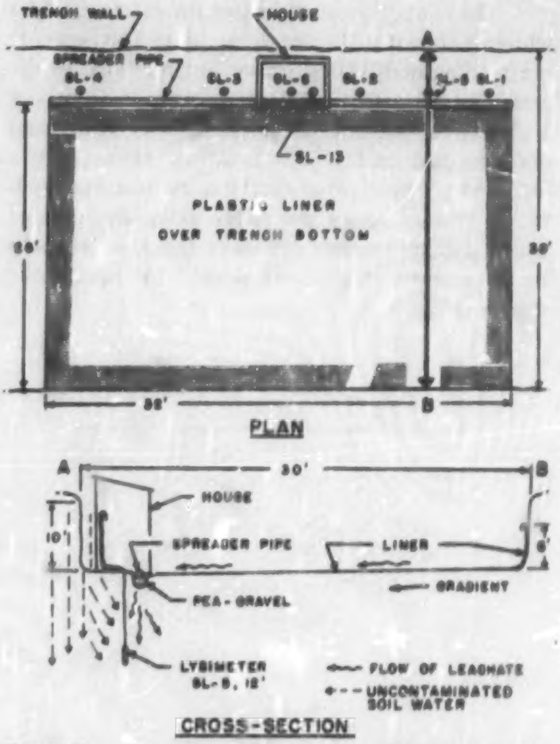
TRENCH WALL
HOUSE
SPREADER PIPE
SL-4
SL-3
SL-6
SL-2
SL-5
SL-1
SL-13
PLASTIC LINER OVER TRENCH BOTTOM
20'
30'
32'
A
B
PLAN
A
30'
B
HOUSE
10'
SPREADER PIPE
LINER
6'
GRADIENT
PEA-GRAVEL
LYSIMETER SL-5, 12'
FLOW OF LEACHATE
UNCONTAMINATED SOIL WATER
CROSS-SECTION

Fig. 4. Plan and cross section of the 1967 cell leachate collection and sampling installation (modified after Lane and Parizek, 1968).

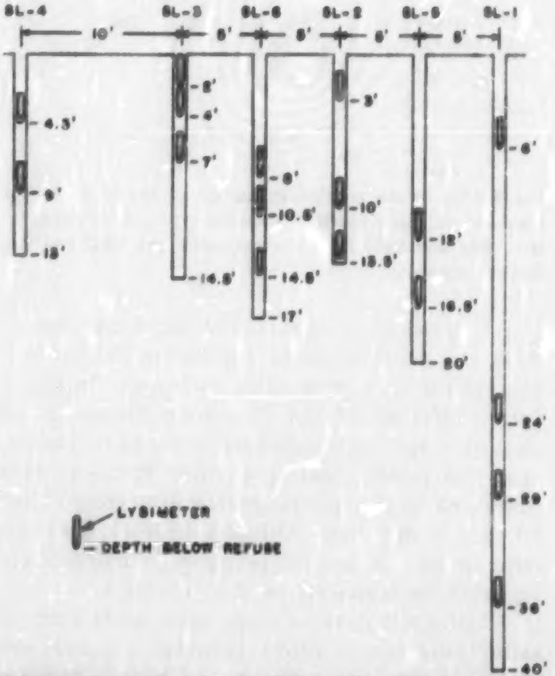
SL-4
SL-3
SL-6
SL-2
SL-5
SL-1
10'
5'
5'
5'
5'
4.5'
9'
13'
2'
4'
7'
14.5'
8'
10.5'
14.5'
17'
3'
10'
13.5'
12'
16.5'
20'
6'
24'
29'
36'
40'
LYSIMETER
DEPTH BELOW REFUSE

Fig. 5. Cross section of the 1967 cell lysimeter network (after Lane and Parizek, 1968).

A second lysimeter network was installed in November 1969 below a landfill trench filled during 1962. Shown in Figure 6 are the relative positions and depths of lysimeters installed in the six boreholes drilled through the refuse. Six-inch steel casing installed in each hole prevented water perched in the refuse from moving down the open holes. Either bentonite pellets or polyester resin (Rohm and Haas P-463) was emplaced at intervals as grout during backfilling of the holes with native soil to isolate the individual lysimeters. Thermistors were also positioned in the holes to measure changes in temperature with time and depth. Sampling and pressure-vacuum tubes for the lysimeters and the thermistor leads were completed just above the land surface in the steel casings which were covered with padlocked, hinged steel caps.

Water ponded in the 1962 cell refuse was sampled from a sump or tap (Figure 2) drilled into the cell, but not through its floor.

The deep monitoring well located in Figure 2 was drilled near the center of the landfill area in November, 1969. Sandy dolomite bedrock was encountered at 51 feet and the water table at 229 feet below the land surface. The six-inch well was drilled by the air rotary method to a depth of 350 feet, and cased to a depth of 185 feet. Groundwater samples for chemical analysis were obtained by bailing or with a submersible pump.

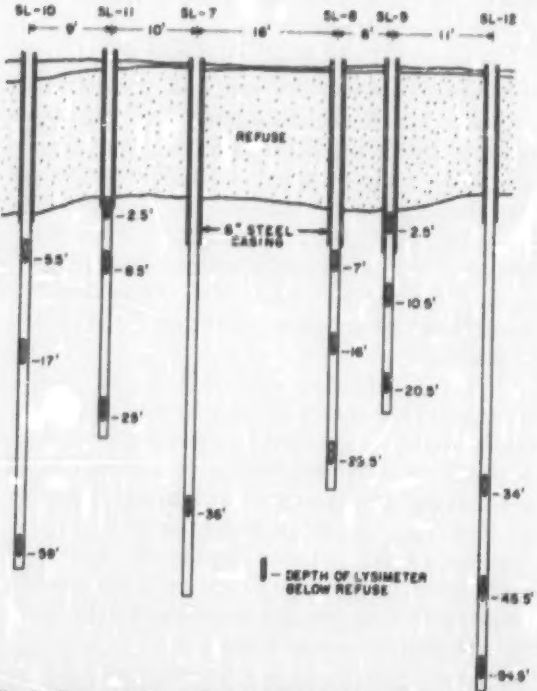

Fig. 6. Cross section of the 1962 cell lysimeter network.

Soil Sampling Methods

Samples for soil chemical analysis were augered from 3 holes beneath the 1967 cell. Holes SL-3 and SL-6 (Figure 4) were augered 5 feet apart in November 1967, before refuse emplacement. Hole SL-13 (Figure 4) was drive cored between these holes to a depth of 9 feet, 2 years after burial of the refuse. Drive cores for soil chemical analysis were also collected in October 1969 from holes SL-10 and SL-12, spaced 52 feet apart along the 1962 landfill trench (Figure 6).

WATER AND SOIL CHEMICAL ANALYSIS

Water Chemical Analysis

Chemical analyses were performed on soil moisture samples extracted from the two lysimeter networks, on leachate bailed from the 1962 cell tap and 1967 sampling house floor, and on groundwater samples from the deep well. Lysimeter samples were collected for analysis approximately every month. The other sources were sampled less often. Routine analyses were made in the field upon sample collection of temperature, pH and Eh (oxidation potential) or DO (dissolved oxygen). The pH was measured with a combination pH-reference electrode and either a Coleman Medallion, or Sargent-Welch Model PBX pH-millivolt meter. Eh was measured using a platinum indicator electrode and saturated KCl calomel reference electrode, with either a Beckman Model G, or Orion Model 407 pH-millivolt meter. Detailed methods of Eh and pH calibration and measurement are described elsewhere (Langmuir, 1971a). DO was measured with a Yellow Springs Model 51 portable oxygen meter. Other analyses run routinely at Penn State included a qualitative description of color, odor, and turbidity, and laboratory analyses of specific conductance with a Beckman conductivity bridge, Model RC-1982, and dipping glass conductivity cell (cell constant near 1 cm^{-1}), and Cl by titration with standard $AgNO_3$ solution (Rainwater and Thatcher, 1960). Total titrable alkalinity (end-point near pH 4.5) was measured with standard H_2SO_4 within 48 hours on samples which were refrigerated upon collection and brought to room temperature just prior to analysis. Samples were also analyzed approximately monthly within a day or two of collection for total Fe, BOD (biochemical oxygen demand), NH_3, and SO_4 by the Pennsylvania Department of Environmental Resources Laboratories in Harrisburg, Pennsylvania. Total Fe was determined on acidified samples by atomic absorption spectrometry, BOD by 5-day incubation of diluted samples, NH_3 by the nesslerization method, and SO_4 by the turbidimetric method. Analyses run bimonthly or less often at Penn State included NO_3 with a specific ion electrode (Langmuir and Jacobson, 1970), and Na, K, and Mg by atomic absorption spectrometry on field acidified samples. Occasional analyses run by the Department of Environmental Resources included NO_2 (sulfanilic acid method), NO (phenoldisulfonic acid method), and PO_4 (stannous chloride method). All analytical techniques employed by the Department of Environmental Resources are described in Standard Methods (1971).

Soil Chemical Analysis

Soil pH, cation exchange capacity, and exchangeable cation analyses were run on soil samples cored from beneath both the 1962 and 1967 refuse cells during installation of the lysimeter networks. Soil pH was recorded as the pH of a 1:1 paste of soil and distilled water. Determination of the exchangeable cations on a soil involves displacement of all adsorbed species with a concentrated extracting solution and application of a correction factor for those cations which entered solution from soluble salts present in the sample. This correction is particularly difficult when the soil moisture in the samples is as high and variable in dissolved solids as landfill leachate. The extracting solution used in this study was 1N NH_4 Ac buffered at pH 7. Correction for soluble salts in contaminated samples was made by washing 30 gram soil samples prior to extraction with either 100 ml of 40% ethanol, or 150 ml of 95% ethanol (Jackson, 1964). The 40% ethanol wash was used to remove Ca, Mg, and K salts from soil samples. Because this wash leached most of the exchangeable Na from the soil, soils to be analyzed for exchangeable Na were instead washed with the 95% ethanol solution.

Cation exchange capacities were obtained by summing the exchangeable cations and the exchangeable acidity. Exchangeable acidity was determined by measuring the pH change of a pH 7 calcium acetate-paranitrophenol extracting solution (Woodruff, 1947).

VARIATIONS IN LEACHATE QUALITY

The Significance of Redox Measurements in Leachate

Water saturation or isolation of refuse materials can prevent contact between atmospheric oxygen or oxygen-rich fresh recharge and biodegradable organics in the refuse. Under such conditions dissolved oxygen in the water and soil moisture is rapidly depleted by aerobic bacteria, and anaerobic decomposition then predominates. In the anaerobic environment iron can exist in its highly soluble and mobile divalent form. Although only total iron analyses are available for leachate samples in this study, previous experience indicates that the iron is present chiefly as ferrous iron and also in part as suspended ferric oxyhydroxides (Langmuir, 1969).

Measurements of DO, or Eh when DO values are less than 0.1 mg/l, and of pH, provide a useful means of explaining the relative and absolute amounts of reduced and oxidized species present in leachate. Eh measurements must be interpreted with caution when made in waters as chemically complex as leachate, however. A measured Eh is the potential at which no net current flows between the platinum indicator electrode and the reference electrode. The net current in solution represents the sum of all anodic and cathodic currents present during measurement (Langmuir, 1971a). Thus, for example, if both dissolved Fe^{2+} and Mn^{2+} are present along with their higher oxides in suspension, the Eh will represent the sum of positive and negative currents for both oxidation-reduction pairs and may thus differ significantly from the measured Eh in a solution containing only the iron species. Such an Eh is called a mixed potential. An additional cause of mixed potentials is the fact that such reactions as the reduction of SO_4 to H_2S, or NO_3 to NH_3 among others are too slow to produce a significant electrode current, whereas rates of oxidation of H_2S or NH_3 are fast enough to produce such a current. Thus, if relatively large concentrations of different oxidized and reduced species are present in a leachate, mixed potential effects may give a measured Eh which has no meaning in terms of the theoretical stabilities of the different species present.

Species which enter into rapid oxidation or reduction reactions that can thus control an Eh measurement are called electroactive. The stability and reproducibility of an Eh measurement depends not only on the presence of electroactive species, but also on their concentrations. Such species are generally absent from oxygenated surface waters (except iron-rich acid mine waters) or aerobic subsurface waters, so that a DO measurement is usually the best indication of the oxidation state of such waters.

Redox conditions in landfill leachates which contain several milligrams per liter BOD or more, are probably controlled in most cases by the presence of ferric oxyhydroxide minerals in the soil, and the activity of anaerobic bacteria. Bacterial activity leads to partial reduction of the oxyhydroxides to Fe^{2+}. Redox conditions then reflect equilibrium between Fe^{2+} and remaining solid or suspended oxyhydroxides as defined by the reversible and electroactive reaction

$$Fe(OH)_3 + 3H^+ + e^- = Fe^{2+} + 3H_2O \qquad (1)$$

where $Fe(OH)_3$ denotes the ferric oxyhydroxides. Because dissolved ferrous iron and suspended or solid ferric oxyhydroxides are abundant and are the predominant electroactive species in contact with most anaerobic landfill leachates, meaningful Eh measurements should often be possible in such waters.

The theoretical Eh-pH boundaries for equilibrium between the important iron and nitrogen species are shown in Figure 7. The dashed lines limit the fields of predominance of NO_3, NO_2, and NH_3 species. These lines show Eh-pH conditions for equal concentrations of nitrate and nitrite, and for nitrite and ammonia, respectively. The solid lines in the Figure denote Eh-pH conditions for equilibrium between suspended or solid ferric oxyhydroxides and dissolved ferrous iron at 0.06 mg/l and 56 mg/l. Also plotted are Eh-pH measurements on a set of leachate samples collected July 22, 1969 from beneath the 1967 landfill cell. Two distinct sample groupings are shown in the Figure. These include a group of analyses which plot along Fe^{2+}-$Fe(OH)_3$ boundaries. Electroactive constituents including iron species are practically absent in the first sample group, so that sample Eh values are only qualitatively meaningful. These samples are relatively aerobic, and may contain DO in excess of 0.1 mg/l. Although small amounts of iron (probably as suspended ferric oxyhydroxides) are present in 5 of these 8 samples, they are otherwise practically free of anaerobic species including ammonia, and contain less than 2 mg/l BOD. Four samples from the 1967 cell are anaerobic with total iron values between 80 and 225 mg/l. Because of their high Fe^{2+} and ferric oxyhydroxide content this sample group plots parallel to Fe^{2+}-$Fe(OH)_3$ boundaries on the diagram. That measured iron concentrations are not exactly consistent with the Fe^{2+}-$Fe(OH)_3$ boundaries in Figure 7 (or Figure 8) is to be expected for these boundaries are based on the activity of Fe^{2+} ion, not the total iron concentration. Also, a particular solubility of $Fe(OH)_3$ is assumed, whereas its solubility will vary widely (Langmuir and Whittemore, 1971). The four contaminated samples in Figure 7 contain a substantial BOD content. The Figure shows why the aqueous nitrogen species likely to occur in anaerobic leachates is ammonia, and why there is no point in analyzing waters high in iron for nitrate or nitrite. The samples plotted in Figure 7 were collected only 7 months after standing water was last observed in fill materials of the 1967 cell.

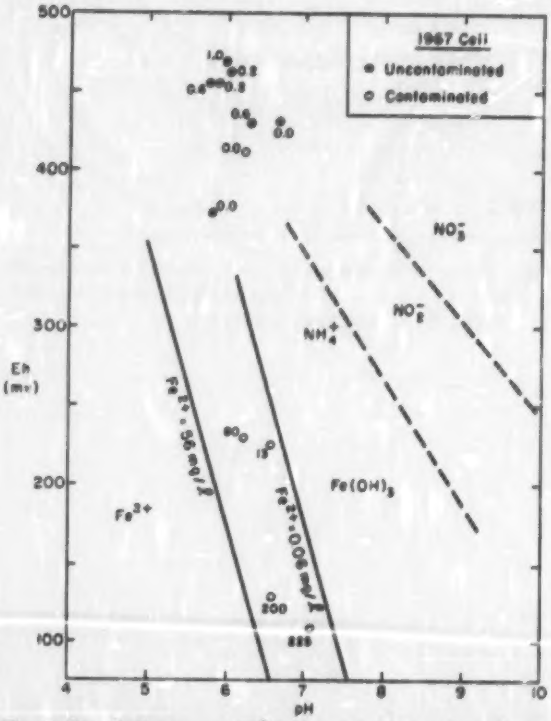

Fig. 7. Eh-pH diagram at 25°C showing fields of predominance of NO_3^-, NO_2^-, and NH_4^+, and boundaries for equilibrium between Fe^{2+} and $Fe(OH)_3$ when Fe^{2+} = 0.06 mg/l and 56 mg/l. A solubility product of $10^{-37.1}$ for $Fe(OH)_3$ is assumed. Also plotted are analyses of samples collected July 22, 1969 from beneath the 1967 cell. Values beside points are total iron concentrations in milligrams per liter. Uncontaminated samples contain BOD < 2 mg/l; contaminated BOD > 2 mg/l.

Figure 8 is a similar plot of Eh-pH measurements on samples collected a year later (July 22-23, 1970) from both the 1967 and 1962 cells. At this time only two of the 1967 cell samples contain significant total iron, and the iron (and BOD) values are generally less than in samples collected a year previous. Ten of the twelve samples from the 1967 installation have Eh's above 390 mv. These samples are now aerobic although most contain substantial amounts of inorganic pollutants. All samples from beneath the 1962 cell plot along Fe^{2+}-$Fe(OH)_3$ boundaries. In general, these samples are anaerobic and contaminated by high total iron, BOD, and ammonia concentrations. Thus, Eh-pH measurements provide insights regarding both the state of renovation of the leachate, and the possible presence of particular oxidized and reduced species.

Time Variations in Leachate Quality Beneath the 1967 Cell

Because samples were not collected from the 1962 instrumented cell until April, 1970, the study of long-term changes in leachate quality is limited to such changes beneath the 1967 cell. The quality of leachates beneath this cell has been greatly influenced by the introduction into the refuse of

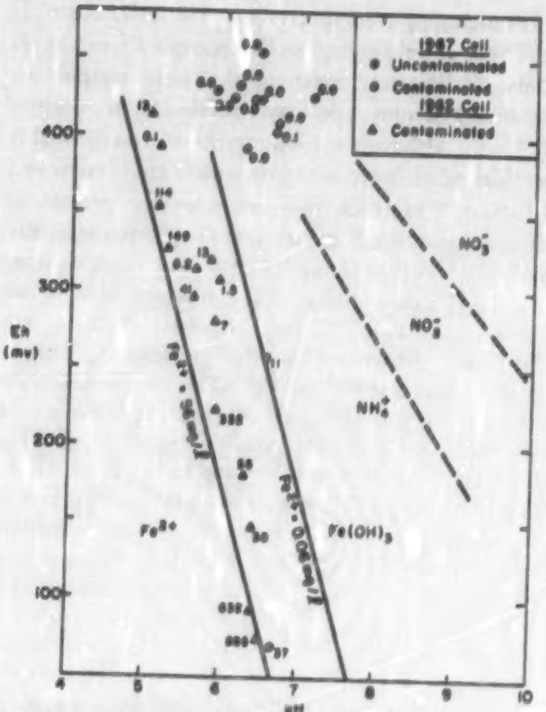

Fig. 8. Eh-pH diagram showing total iron values in samples from beneath the 1962 and 1967 refuse cells on July 22-23, 1970. See explanation for Figure 7.

about 8 inches of artificial recharge, and about 6 inches of natural precipitation as rain, between October 30, 1967, and April 28, 1968 (Lane, 1969). The artificial recharge was taken from a public water-supply well of the Pennsylvania State University. This well is also in the Gatesburg Formation, and its water probably had a composition similar to that from well UN-17 (see Table 4). This 14-inch total constituted perhaps more than double the amount of water which might be expected to infiltrate this refuse cell naturally during a similar 6-month period. As a consequence, water stood in the bottom of the sampling house (Figure 4) from May through December, 1968.

Time plots at four different depths of changes in specific conductance, Cl, BOD, NH_3-N, and total Fe, are shown in Figures 9-13 respectively. Data used to construct the plots for dates before August 1968 are from Lane (1969). The plots show that leachate moved to the shallowest lysimeters before flooding of the cell, and almost immediately after refuse emplacement on October 30, 1967. This partly reflects compaction during emplacement, and the high (over 55%) initial water content of the refuse (Lane and Parizek, 1968), but may also have been caused by polluted surface runoff which flooded the open lysimeter holes shortly before refuse emplacement (Lane, 1969).

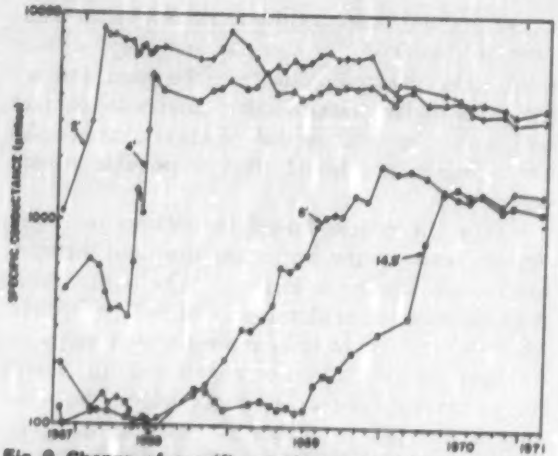

Fig. 9. Change of specific conductance with time in soil moisture from 2 and 4 feet depths (SL-3) and 8 and 14.5 feet depths (SL-6) beneath the 1967 cell.

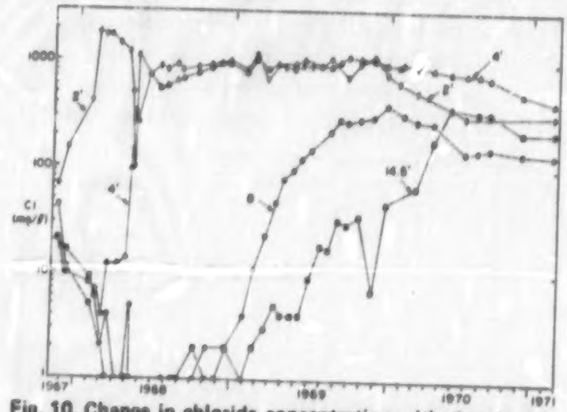

Fig. 10. Change in chloride concentration with time in soil moisture from 2 and 4 feet depths (SL-3) and 8 and 14.5 feet depths (SL-6) beneath the 1967 cell.

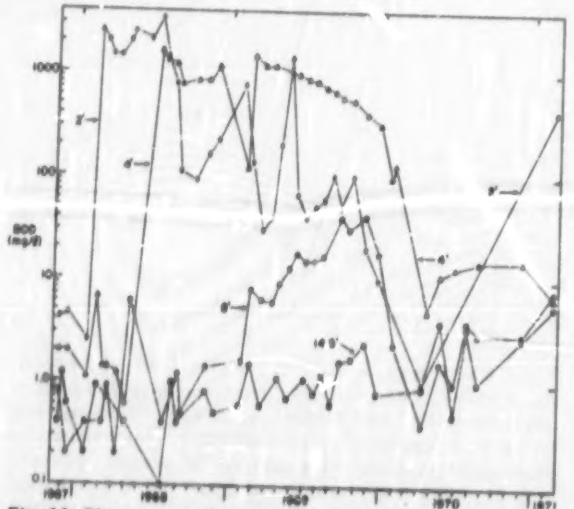

Fig. 11. Change in BOD with time in soil moisture from 2 and 4 feet depths (SL-3) and 8 and 14.5 feet depths (SL-6) beneath the 1967 cell.

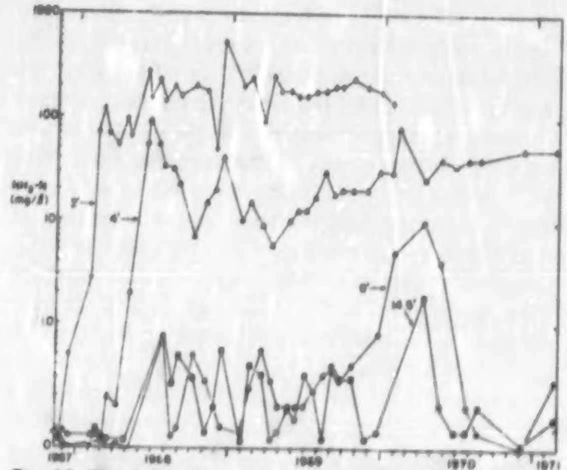

Fig. 12. Change in NH_3-N with time in soil moisture from 2 and 4 feet depths (SL-3) and 8 and 14.5 feet depths (SL-6) beneath the 1967 cell.

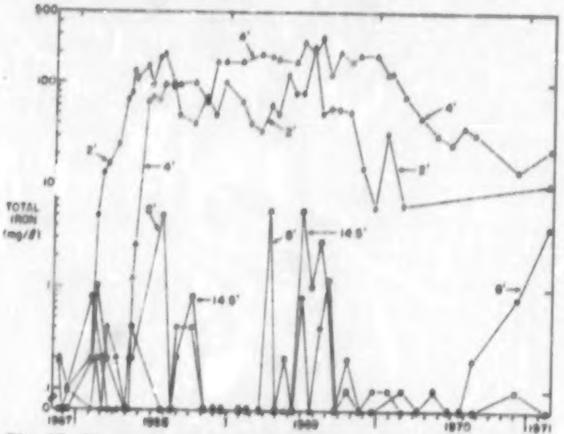

Fig. 13. Change in total iron with time in soil moisture from 2 and 4 feet depths (SL-3) and 8 and 14.5 feet depths (SL-6) beneath the 1967 cell.

The concentration-time plots show that maximum specific conductance and Cl values arrived simultaneously at each of the 4 lysimeter depths. These maxima were 8445 μmhos and 1890 mg/l respectively, at the 2 feet depth after 4 months, and 1470 μmhos and 375 mg/l respectively, at the 14.5 feet depth after 31-32 months. Thus, by the time the leachate reached 14.5 feet, maximum conductance and Cl values had decreased by 83% and 80% respectively. The plots show that maximum contaminant values are moving downward at the rate of approximately 6 ft/yr.

Chloride and the majority of other species (chiefly inorganics) which contribute to the conductance, are readily leached from the refuse into the subsoil after the refuse has attained field capacity. Because Cl is practically unaffected by reactions in the soil, its decrease with depth must be caused by dispersion and dilution. Dilution is favored by the design of the 1967 sampling installation which permits fresh recharge to infiltrate the soil adjacent to the sampling house where it can percolate downward and dilute the leachate (Figure 4).

The behavior of redox-sensitive species including BOD, total iron, and ammonia (Figures 11-13) is more complex and less systematic with depth than that of specific conductance or chloride. This is partly because conditions in unsaturated soils can be both aerobic and anaerobic within a short distance. Initial conditions in the soil at first sampling in November 1967 were aerobic as evidenced by maximum concentrations of 11 mg/l NO_3-N, 1.0 mg/l NO_2-N, and negligible ammonia and iron concentrations (Lane, 1969). A BOD value of 2500 mg/l arrived at the 2 feet depth after 4 months, and a maximum BOD of 1600 mg/l at 4 feet after 8-9 months. With the earlier arrival of leachate containing a few milligrams per liter BOD, anaerobic conditions were initiated, and bacterial reduction of nitrate and nitrite to ammonia ensued by reactions such as

$$NO_3^- + CH_2O + 5H^+ + 4e^- = NH_4OH + HCO_3^- + H_2O \quad . \; . \; . \; . \; . \; (2)$$

where CH_2O represents the organic matter in BOD. Reduction reactions such as (2) raise pH and probably account for the maximal pH values of 6.5 and 7.5-8.5 observed in the simulated landfill studies of Quasim and Burchinal (1970), and Fungaroli and Steiner (1971), respectively. Maximum pH's between 7.3 and 8.6 were also observed in this study near the time when conditions in the soil were changing from aerobic to anaerobic. The relatively lower pH maximum of Quasim and Burchinal reflects the absence of soils and other materials in their purely organic refuse which could adsorb or otherwise react with H ions.

Although small amounts of ammonia were formed by reduction of initially present NO_3 and NO_2, ammonia has chiefly been produced by the decomposition of nitrogenous organic substances in the refuse and leachate. Maximum ammonia nitrogen values of 100 mg/l or more arrived at the 2 and 4 feet depths simultaneously with the BOD maxima. Insufficient sample was available for analysis from the 2 feet depth after January 1970. The gradual increase in NH_3-N at 4 feet after October 1968 may be caused by its production from the breakdown of organic nitrogen in the leachate.

Because leachate which contains nitrate or nitrite is not sufficiently reduced to contain ferrous iron from the solution and reduction of ferric oxyhydroxides in the soil, the buildup of total iron (chiefly Fe(II)) by leaching of the soil could not occur until the onset of more reducing conditions. As a result, maximum total iron values of 100 mg/l or more do not reach the 2 and 4 feet depths until about 1 month after the arrival of maximum ammonia values at these depths. The behavior of iron and ammonia at 8 and 14.5 feet depths is less easily explained, although clearly a major reduction in these species has occurred with depth. Maximum total iron values at 2 and 14.5 feet depths were 225 and 5.6 mg/l respectively, and represent a reduction of 97.5%. Maximum ammonia values at 2 and 14.5 feet were 540 and 1.8 mg/l—equivalent to a reduction of more than 99%.

In their studies of synthetic landfills Quasim and Burchinal (1970) and Fungaroli and Steiner (1971) observed maximal iron concentrations at the lowest observed pH's. A maximum total iron of 850 mg/l was detected at pH 5.4 in Quasim and Burchinal's study. Fungaroli and Steiner measured total iron maxima of 1700-1800 mg/l at a pH of about 5.5. Examination of the data plotted in Figures 7 and 8 shows that in an actual landfill, total iron concentrations also depend on the oxidation state of the system, and in fact that maximum total iron values do not occur at the lowest pH's but at intermediate values.

Probably most of the water entering the refuse and subsoil before 1970 was from the equivalent of 14 inches of rain added to the refuse prior to May, 1968. Heavy rains in the spring of 1970 increased the moisture content of the refuse to well above field capacity for the first time since 1968, and re-established strongly anaerobic conditions. That no increase in specific conductance or chloride resulted from this development shows that the concentrations of soluble inorganic species in the refuse had been significantly depleted. However, increases in BOD, ammonia, and iron during 1970 show that biodegradable organic material is still present and can be released from the refuse when its moisture content approaches saturation.

Differences Between the 1962 and 1967 Sampling Installations

Before a useful comparison can be made of changes in the 1962 and 1967 cell leachates with time and depth, a discussion of differences in the two cell installations and settings is necessary. Features of the 1967 sampling system have probably accelerated the oxidation and dilution of leachates in the subsoil with the result that more leachate renovation is occurring than could be expected under more typical conditions in the landfill. As shown in Figure 4, all leachate produced in the cell percolates through a trench down into the soil and to the lysimeters below. Oxidation of leachate is possible in both the trench, which can receive oxygen through the sampling house, and in soils beneath the trench which are adjacent to unsaturated soils under the trench liner. Also, oxygen in fresh percolation waters can flow through the inter-trench space next to the sampling shed. This fresh soil water will also have a diluting effect on leachate quality. Soil moisture at the lysimeters is thus a mixture of leachate from the cell and fresh percolation waters. Also, because of its upslope position (Figure 2) the 1967 cell is well drained and cannot intercept appreciable quantities of leachate from adjacent cells.

In contrast the 1962 cell is emplaced in a relatively low-lying area where concentration of precontaminated surface runoff from adjacent slopes frequently occurs, and repeatedly water-saturates the fill. This increases the volume of leachate production and isolates the soil from fresh sources of oxygen so that anaerobic conditions are established both in the fill and at depth beneath it. The poor quality and large volume of leachate is further aggravated by downslope movement of leachates from adjacent landfill cells along the cell floors. Downslope movement and concentration of leachate may also follow bedrock surfaces beneath the soil which in this case roughly parallel the topography.

The above conditions have led to relatively larger amounts of BOD in leachate beneath the

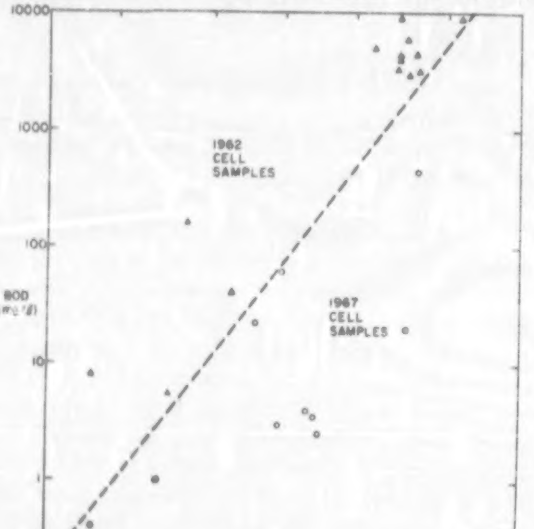

Fig. 14. Comparison of the BOD and specific conductance of leachates from beneath the 1962 and 1967 refuse cells on July 22-23, 1970. Solid circles denote uncontaminated samples (< 2 mg/l BOD); open symbols denote contaminated samples (> 2 mg/l BOD).

1962 cell than under the 1967 cell. This difference is evident from Figure 14 which shows the contribution of BOD to the specific conductance of leachates collected from beneath the two cells on July 22-23, 1970.

Leachates in Refuse of the 1962 and 1967 Cells

A comparison of the quality of standing water in refuse from the 1962 cell tap, and standing water from the floor of the 1967 cell sampling house is given in Table 2. The data show that soluble inorganic species have been relatively depleted from the 1962-dated refuse during the 8 years since its burial. Thus, Na, K, Ca, and Cl concentrations were 89 to 66% lower in waters standing in the 1962 refuse than in waters within the 1967 refuse at the times of sampling. This reduction in soluble inorganic species has not been accompanied by a drop in BOD values which are practically equal in the two leachates.

Leachate Quality Versus Depth Under the 1962 and 1967 Cells

Plots of the chemical quality of leachates beneath the two cells on July 22-23, 1970 are shown in Figures 15-20. Also shown in each Figure is a schematic profile with the general slope settings of the two cells. Specific conductance and chloride profiles beneath both cells display the same general trends. However, because chloride is among the species most readily leached through the soil, chloride values exaggerate trends shown by the conductance. The Figures show that concentrations of chloride and total ionic species (as conductance) released from the 1967 refuse have just begun to drop, but have been decreasing for several years under the 1962 cell. The leachate front beneath the 1962 refuse has moved about 50 feet in 8 years, or at an average rate of 6 ft/yr. Under the 1967 installation the leachate front is moving at an average rate of 11 ft/yr, and has reached about the 30 feet depth after 2 years and 9 months. This may be compared to the 6 ft/yr vertical movement rate of maximum conductance and chloride values under the 1967 cell. In the absence of long-term records for the 1962 cell it is not possible to examine the effects of dilution or dispersion on conductance and Cl values with depth. Data already described indicates that such processes have produced a significant reduction in conductance and Cl values with depth beneath the 1967 cell.

Table 2. Comparison of the Quality of Leachates Standing in Refuse in the 1962 and 1967 Cells (The 1967 cell pit bottom sample analysis is from Lane (1969). Specific conductance (μ) is in micromhos at 25°C. Other analyses are in milligrams per liter unless otherwise noted)

	1967 Cell Pit Bottom Collection Date 6/15/68	*1962 Cell Tap Sample Collection Date 7/22/70*
T (°C)	–	15.1
Eh (mv)	–	+82
pH	–	6.49
μ	6,280	2,290
Cl	657	225
SO_4	--	50
NO_3-N	0.0	0.0
NO_2-N	0.18	–
NH_3-N	60	18
Alkalinity as HCO_3 (pH 4.5)	–	502
PO_4	0.8	0.0
BOD	1,820	1,880
Ca	1,040	186
Mg	–	37
Na	350	39
K	160	51
Total Fe	128	578

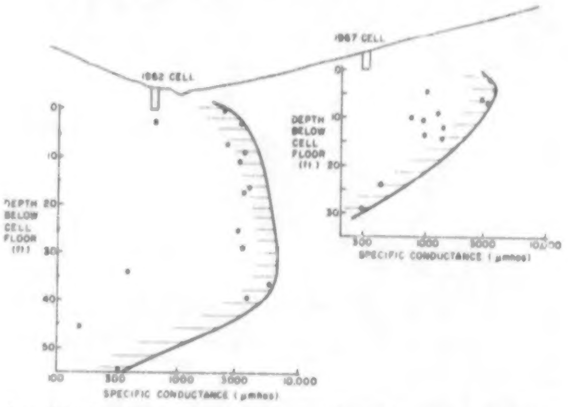

Fig. 15. Specific conductance in leachates beneath the 1962 and 1967 cells, July 22-23, 1970.

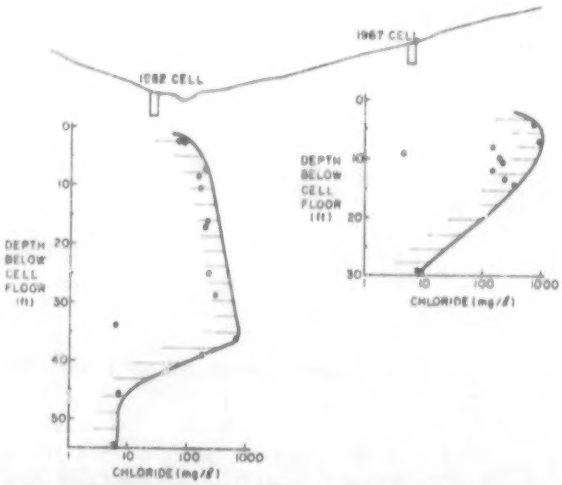

Fig. 16. Chloride concentrations in leachate beneath the 1962 and 1967 cells, July 22-23, 1970.

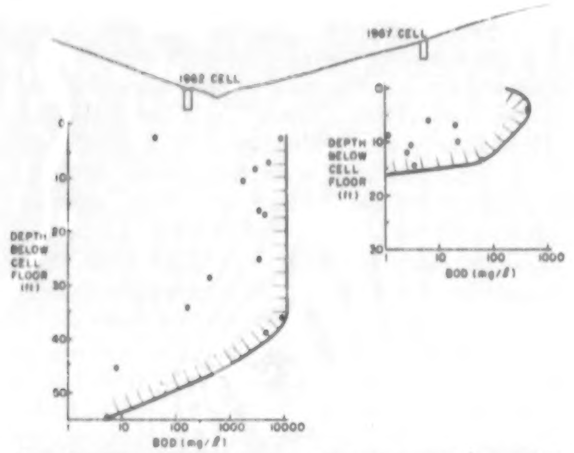

Fig. 17. BOD concentrations in leachate beneath the 1962 and 1967 cells, July 22-23, 1970.

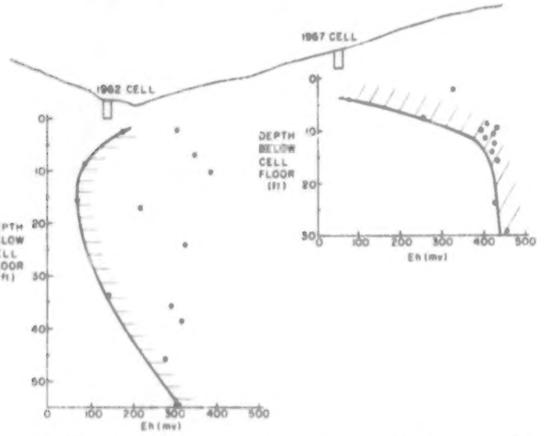

Fig. 18. The Eh of leachate beneath the 1962 and 1967 cells, July 22-23, 1970.

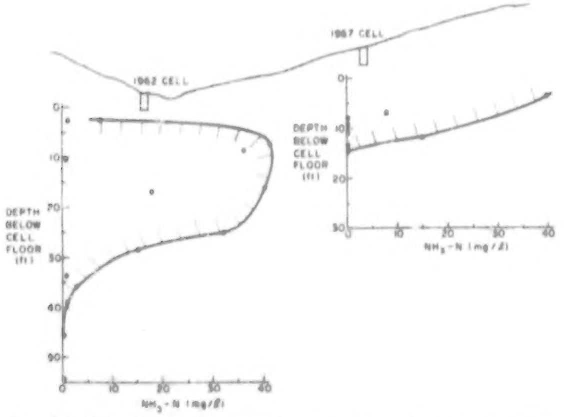

Fig. 19. NH_3-N in leachate beneath the 1962 and 1967 cells, July 22-23, 1970.

BOD concentrations beneath the 1962 trench (Figure 17) roughly parallel conductance values and show that largely anaerobic conditions exist to depths near 50 feet. This is because most infiltrating water in the vicinity of this cell has been contaminated by contact with refuse. As yet no obvious reduction in the BOD released from the refuse is apparent. However, the most anaerobic leachate is not directly under the cell but at a depth of 10-15 feet based on the occurrence at this depth of minimum Eh (Figure 18) and maximum NH_3-N (Figure 19) and total Fe values (Figure 20). The presence of relatively more aerobic leachates above 10-15 feet indicates that significant depletion of biodegradable organic materials in the 1962-dated refuse is occurring.

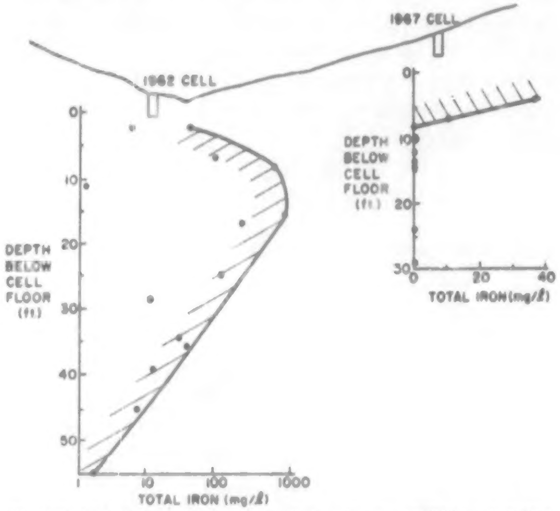

Fig. 20. Total iron in leachate beneath the 1962 and 1967 cells, July 22-23, 1970.

BOD values issuing from the 1967 refuse cell have not yet significantly decreased. Because of relatively oxidizing conditions under this cell, BOD's become oxidized and depleted 10-15 feet above the deepest penetration of the leachate. The lowest Eh's are directly beneath the 1967 cell refuse. At greater depths conditions become more oxidizing. A lowering in the capacity of the 1967 refuse to release reduced species has not yet occurred. This is further evident from the plots of NH_3-N and total Fe which show maxima for these species directly below the 1967 cell.

The occurrence of the ammonia maximum at 8 feet and iron maximum at 12 feet below the 1962 site is consistent with the Eh drop over this depth interval. Iron values in excess of 10 mg/l and Eh's less than 200 mv are present to depths of 45 feet below the 1962 cell. Under these conditions ammonia is the stable nitrogen species and in fact no nitrate or nitrite has been detected at these depths. However, Figure 19 shows a rapid decrease in ammonia below 25 feet. Explanation for this decrease may be retardation of the ammonia caused by bacterial assimilation, or ammonia adsorption by clays in the subsoil. The decrease in iron with depth may also in part reflect cation exchange on clays, but probably is caused chiefly by oxidation of the leachate with depth.

Under the 1967 cell, ammonia concentrations are present at greater depths than are total iron values. The absence of nitrate or nitrite beneath this cell indicates that elimination of the ammonia is also either by bacterial assimilation or cation exchange. The rapid increase in Eh and drop in iron under this cell is most consistent with removal of the iron by oxidation to ferric oxyhydroxides.

ION EXCHANGE ON SOILS BENEATH THE LANDFILL

Soils beneath the State College Regional Sanitary Landfill have clay contents ranging from 2 to 41% by weight (Lane, 1969). The ability of these soils to renovate or alter leachate quality in large part depends on their ion exchange behavior, which in turn depends on the mineralogy of the clay-sized soil fraction. In Gatesburg-type soils this is chiefly kaolinite (75-80%), illite (5-10%), montmorillonite (5%), vermiculite (0-5%), and chlorite (0-5%) (Lane, 1969), and ferric oxyhydroxides which comprise from about 0.2 to 1.0% of the total soil weight (Matelski et al., 1963).

The role of cation exchange in leachate interaction with uncontaminated soils depends on differences in the absolute and relative concentrations of cations in the leachate and in uncontaminated soil moisture. A comparison of typical cation concentrations in soil moisture before and after contamination is given in Table 3.

Chemical analyses were made of uncontaminated soils in cores SL-3 and SL-6 taken at depths from 3 to 15-17 feet beneath the 1967 refuse cell (Figure 5). The analyses showed pH values to increase with depth from about 4.7 to 5.7. The concentration of total exchangeable bases ranged from 0.7 to 1.6 meq/100 g of soil; the cation exchange capacity from 1.7 to 5.0 meq/100 g of soil. The order of adsorption of cations was generally H ≫ Ca ≈ Mg > Na > K at all depths. With the exception of H ions, this is the same general order of cation concentrations in uncontaminated soil moisture.

Table 3. Quality of Soil Moisture Collected from Suction Lysimeters Beneath the Landfill (Concentrations are in milli-equivalents per liter)

Cation	*Uncontaminated*	*Contaminated, beneath 1967 cell*	*Contaminated, beneath 1962 cell*
Ca	0.6 -1.0	0.2- 3	10 -25
Mg	0.5 -1.0	0.2-10	7 -20
Na	0.05-0.2	10 -40	4 -10
K	0.05-0.2	5 -10	0.1- 2.5

Cation concentrations in contaminated soil moisture under the 1967 cell are in the decreasing order Na > K > Mg > Ca, and leachate pH's generally range from 6.1 to 7.1. The order of adsorbed cations on soils from leachate-contaminated core SL-13, at depths from 2-7 feet was generally H > Na ≫ Ca > Mg > K, with soil pH values decreasing with depth from 7.2 to 4.6. Total exchangeable bases ranged from 1.3 to 2.8 meq/100 g; the cation exchange capacity from 1.7 to 4.2 meq/100 g. Significantly, the adsorbed Na content increased from about 0.2 meq/100 g in uncontaminated soil to 0.6-0.8 meq/100 g in leachate-affected soil. The Na fraction of total exchangeable bases increased from 12-24% in uncontaminated soil to 29-46% in contaminated soil.

High soil pH's (8.2) and high Ca content (2.5 meq/100 g) of soils directly beneath the 1967 cell were evidently caused by the complete solution of the overlying concrete floor of the sampling shed by leachate. This resulted in precipitation of $CaCO_3$ in soil above the 2 feet depth as evidenced by soil effervescence in HCl, and calculated saturation of soil moisture with respect of $CaCO_3$ (calcite). A further effect has been reduction of Ca values in the leachate which has increased the relative predominance of Na in the leachate resulting in higher Na adsorption by the soil.

Because refuse in the 1962 cell has been relatively depleted in the most soluble inorganic species after 8 years of leaching, the order of cation concentrations in leachate under the cell was Ca ≈ Mg > Na ≫ K. The pH of leachates ranged from 5.1 to 6.5. The order of adsorbed cations on contaminated soils from cores SL-10 (4-42 feet) and SL-12 (4-56 feet) was generally H ≫ Ca ≫ Mg > Na > K, with soil pH values from 4.8 to 6.7. Total exchangeable bases ranged from 1.0 to 2.9 meq/100 g, the cation exchange capacity from 1.2 to 4.8 meq/100 g.

Unfortunately, exchangeable base measurements were not made of adsorbed ammonia and ferrous iron, although these species may be as important as the species measured on some clays contaminated by landfill leachate (Toth and Ott, 1970).

Probably the most significant result of the cation exchange study was the observation that the percent base saturation at a given pH is significantly higher in leachate-contaminated soils than in uncontaminated soils (Figure 21). This could be expected in that the amount of exchange depends on the concentrations of metal cations relative to H ion

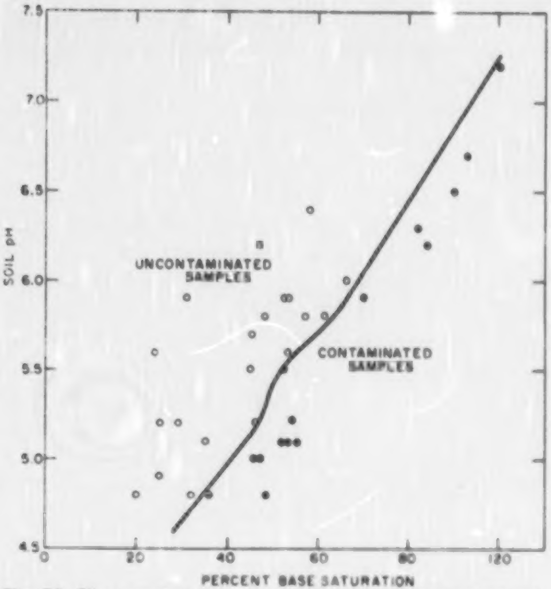

Fig. 21. The percent base saturation of leachate-contaminated, and uncontaminated soils beneath the landfill.

concentrations, and the former are more concentrated in leachate than in uncontaminated soil moisture at comparable pH's.

The pattern of Cl and SO_4 concentrations below the 1962 cell suggests that SO_4 is being removed from the leachate with depth. Thus, at the 2 feet depth, SO_4 and Cl values are about 2 and 3 meq/l respectively, whereas SO_4 decreases systematically to about 0.5 meq/l and Cl increases to 7 meq/l at a depth of 36 feet beneath the cell. Removal of SO_4 is probably not by bacterial reduction in that redox conditions are not sufficiently anaerobic, but may be caused by anion exchange on clays. Kaolinite has an exchange capacity of about 6 meq/100 g for SO_4 at pH 6 (Wiklander, 1964). Therefore a soil with 20-30% kaolinite would have an adsorption capacity for SO_4 of 1.2-2.0 meq/100 g. Sulfate might be adsorbed at approximately this concentration when anions such as PO_4 which are more preferentially adsorbed than SO_4 are not present in the leachate. However, clogging of exchange sites by organic anions, and by ferric and manganese oxyhydroxides probably reduces the number of sites available for sulfate exchange.

PHOSPHORUS VARIATION IN SOILS BENEATH THE LANDFILL

In uncontaminated soils, phosphorus is adsorbed on clays and present as calcium, magnesium, ferric and aluminum phosphates. Phosphate concentrations in the leachate were consistently below the limits of detection (0.05 mg/l at PO_4). Extractable phosphorus was determined in soil samples collected from beneath the 1962 and 1967 refuse cells with a solution of 0.025 N HCl and 0.03 N NH_4F (Bray and Kurtz, 1945). This method removes P in exchangeable positions on clay, readily acid-soluble forms of P (chiefly Ca phosphates), and a portion of the iron and aluminum phosphates. As shown in Figure 22, at each depth more extractable phosphorus was present before than after leachate had percolated through the soil. The reduction in extractable phosphorus is probably caused by its precipitation as relatively insoluble ferric iron and aluminum phosphates.

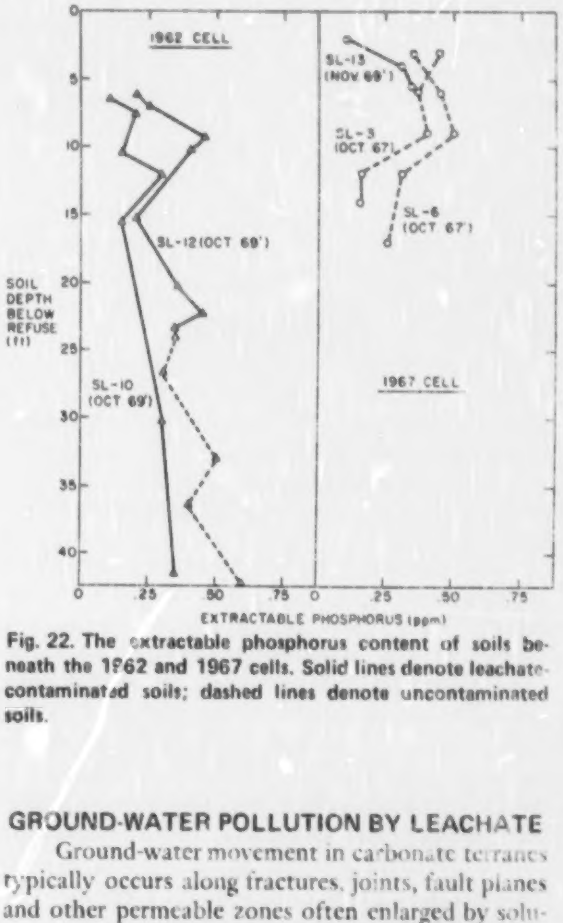

Fig. 22. The extractable phosphorus content of soils beneath the 1962 and 1967 cells. Solid lines denote leachate-contaminated soils; dashed lines denote uncontaminated soils.

GROUND-WATER POLLUTION BY LEACHATE

Ground-water movement in carbonate terranes typically occurs along fractures, joints, fault planes and other permeable zones often enlarged by solution of the rock. The Upper Sandy Member of the Gatesburg Formation is an interbedded sequence of carbonate-cemented quartz sandstones and dolomites which has a greater average primary permeability than other more pure dolomite aquifers in the study area. Because of this high relative permeability, a water table map of the area surrounding the landfill site (Figure 23) shows a ground-water trough in the Upper Sandy Member. The trough coincides with a topographic high, as the quartz in the Upper Sandy Member causes it to be more resistant to erosion than more pure adjacent carbonate rocks. Water table contours in Figure 23 show that the direction of ground-water flow beneath the landfill is probably northwest into the ground-water trough. The exact direction of ground-water flow may not be at right angles to the water level contours in that permeabilities in carbonate rocks are highly anisotrophic (Davis and DeWiest, 1966).

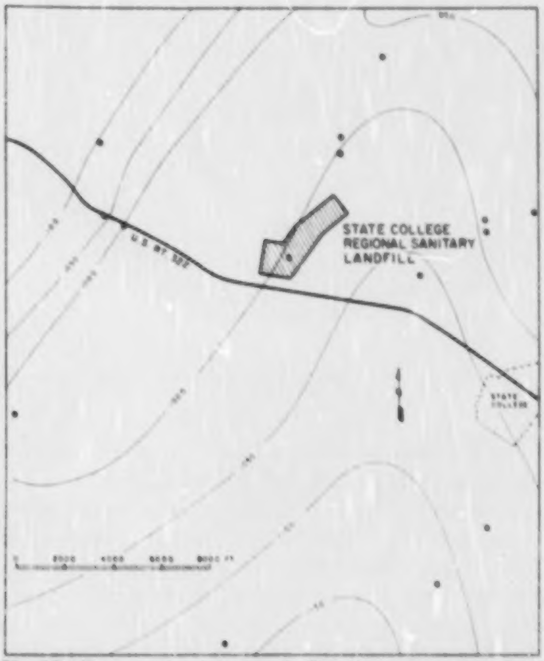

Fig. 23. Water table elevation in feet above mean sea level in the vicinity of the State College Regional Sanitary Landfill, June 3-7, 1971.

A deep water table well was drilled on a fracture trace in November, 1969, in the center of the landfill property (Figure 2). Fracture traces are natural linear features mappable on aerial photographs which represent the surface expressions of near-vertical fracture zones along which permeability is usually much higher than in the surrounding rock (Lattman and Parizek, 1964). Water from such a permeable zone should be more representative of the local ground-water depth and quality than water obtained from tighter interfracture trace areas.

During the first year of observation, ground-water levels in this well (Figure 24) showed gradual seasonal trends independent of individual precipitation events. In this respect the well was typical of other wells located on Gatesburg Ridge along this section of the valley (Giddings, 1971). Thus, the gradual rise in water level beginning in March, 1970 presumably corresponds to ground-water recharge which entered the subsurface in the fall of 1969 or of a previous year.

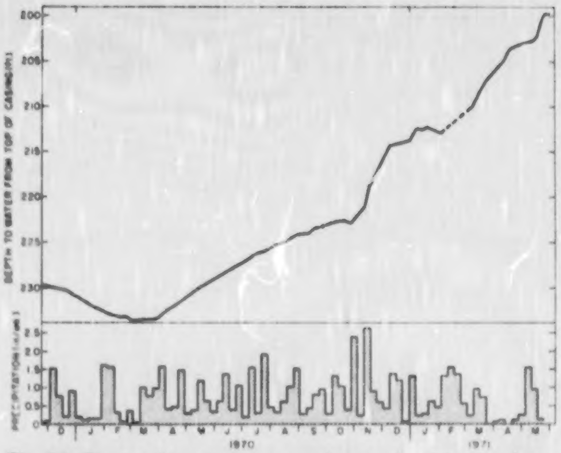

Fig. 24. Fluctuations in the ground-water level in the deep well, and precipitation recorded at the State College Regional Sanitary Landfill from November, 1969 to June, 1971.

Since early November, 1970, however, a sharp continuous rise of the water table has occurred in response to heavy rains. This shift in recharge characteristics may have been caused by the washing away of a fine-grained detrital plug which had partially sealed a sinkhole immediately upvalley from most of the landfill area ("sink area" in Figure 2). This now enables runoff from Park Forest Village, a housing development 500 feet southwest of the landfill property, to move rapidly into the subsurface at this point. The specific conductance of storm runoff from Park Forest Village along this gulley ranged from less than 100 μmhos during summer thunderstorms in 1970 to nearly 600 μmhos following the November 15th rainfall. Although some contamination in the present landfill well water may be from this source, such recharge could be preventing severe contamination of the ground water by landfill leachate.

Another possible source of pollution in the well water is a sewage oxidation lagoon about 1000 feet from the well (Figure 2) which operated from 1967 to 1969, and serviced about 1000 people.

The quality of water from the landfill well is given in Table 4. With specific conductances between 800 and 995 micromhos, and a DO content of 2.3 mg/l or less, measured in 1970, this ground water was more polluted than any other pumped from nearly 200 wells in carbonate rocks within ten miles of the landfill site (Langmuir, 1971b). Conductances of waters from 4 other wells which

Table 4. Background Ground-Water Quality in the Upper Sandy Member of the Gatesburg Formation (Well UN-17), and the Quality of Ground Water from the Well at the Landfill Site (Specific conductance (μ) is in micromhos at 25°C. Other analyses are in milligrams per liter unless otherwise indicated)

	UN-17	*LANDFILL WELL*						
Collection date	*8-27-70*	*4-23-70*	*4-30-70*	*5-27-70*	*8-13-70*	*9-23-70*	*12-31-70*	*5-29-71*
Appearance & odor	*clear, odorless*	*clear, odorless*	*clear, odorless*	*clear, odorless*	*slight turbidity, odorless*	*slight turbidity, odorless*	*clear, odorless*	*clear, musty leachate odor*
T (° C)	9.5				10.0	9.3		10.0
DO (% sat'n)	93				21			< 1
Eh (mv)						268		46
pH	8.04				6.89	6.53	7.50	7.31
μ	215	995	860	800	890	913	810	950
BOD					1.1	0.8		7.5
Cl	1.7	41	23		41	32	26	50
SO_4	8		17		22	30		42
Alkalinity as HCO_3 (pH 4.5)	128	300	278	450	485	449	520	463
NO_3-N	1.5	1.8	2.2		1.5	0.9		0.8
NH_3-N						0.5		0.8
Fe (total)					0.4	0.7		2.1
Ca	22	13			14			
Mg	15	92			84			
Na	0.5	22			46			
K	0.7	4.0			9.7			

also tap the Upper Sandy Member range from 182 to 345 μmhos. The closest of these wells has the best quality water and is about ¾ mile from the landfill. A comparison of the quality of water from the landfill well with that from an uncontaminated well (UN-17) in the Upper Sandy Member representing background quality, is presented in Table 4. The Table also shows that gradual deterioration of the quality of water in the landfill well is occurring with time. The analysis in May 1971 shows the ground water to be anaerobic and to contain significant amounts of BOD, total iron, and ammonia. Other contaminant species present in abnormal amounts are Cl, SO_4, and HCO_3. This latest deterioration in quality is evidently caused by mixing with leachate from the landfill.

Results of a 21-hour pump test of the 6-inch diameter landfill well at 10 gpm on May 28-29, 1971 indicate that the transmissivity of the underlying formation is about 4500 gpd/ft. This is consistent with transmissivities for the Upper Sandy Member measured by Siddiqui (1969) of 260-620 gpd/ft in 2 nonfracture trace wells, 370-68,400 gpd/ft in 10 wells on single fracture traces, and 2310-423,000 gpd/ft in 11 wells on fracture trace intersections. These data demonstrate the extreme anisotropy of flows in carbonate bedrock and the difficulty of predicting ground-water flow volumes through a given rock section.

The residual soils at the landfill site are too heterogeneous to permit meaningful physical calculations of rates of leachate flow through them under saturated conditions. The best method of following leachate progress through the soil is from the chemical data which indicate that the leachate front is moving downward at 6-11 ft/yr, but has not reached bedrock beneath the two lysimeter networks.

Because ground water under the landfill has evidently become polluted by leachates from the buried refuse, channelling of leachate down fractures in shallow bedrock must be occurring. Leachate may also reach the ground-water table when contaminated landfill runoff infiltrates the sandy stream bottom or enters sinkholes in the sink area (Figure 2) at times of heavy storms.

CONCLUSIONS AND RECOMMENDATIONS

Results of this and previous studies support the following generalizations and suggestions:

1. In a landfill in unsaturated soils, topography will be the chief control on the amount and character of moisture entering the refuse. Refuse cells on hill slopes will generally receive less infiltration and less precontaminated moisture from adjacent cells, so that their leachates will have lower BOD, iron and ammonia concentrations than leachates from cells located near valley bottoms. Cells near valley

bottoms are likely to produce highly contaminated anaerobic leachate which is not effectively renovated during movement through 40 or more feet of soil.

2. Marked decreases in the amounts of leachate contaminants can occur with movement of the leachate in unsaturated soils on hill slopes. In study area subsoils the decrease in Cl and a similar reduction in other species is caused by dilution and dispersion. The PO_4 decrease results chiefly from its precipitation as ferric and aluminum phosphates. Oxidation causes a reduction in BOD and ferrous iron. Ion exchange on soil colloids decreases SO_4 and metal cation values generally. The reduction in ammonia with depth is also caused by cation exchange, or by bacterial assimilation. Physical filtration by soil removes bacteria, ferric oxyhydroxides, and other suspended substances from the leachate.

3. Inorganic salts progressively decrease in concentration in leachate as they are depleted in the refuse. However, BOD and associated reduced species including ferrous iron and ammonia, fluctuate in amount in leachate with changes in the water content and temperature of the refuse.

4. Eh measurements in leachate are often meaningful, for leachate is typically poised by the presence of abundant ferrous iron and suspended or soil ferric oxyhydroxides. Along with pH, such measurements are useful in predicting the presence and mobility of redox sensitive species in the leachate.

5. In unsaturated soils leachate quality can be improved if undisturbed strips of soil several feet wide are left between landfill cells so that fresh recharge can enter the subsurface and dilute and oxidize the leachate.

6. Improvement in leachate quality will also occur if concrete demolition wastes are placed in the bottom of landfill trenches. These lime-rich wastes tend to raise leachate pH and precipitate leachate Ca as $CaCO_3$. The pH increase leads to an increased base exchange capacity of the soil and thus to increased adsorption by the soil of remaining cations in the leachate.

7. This study and that of Hughes et al. (1971) indicates that location of landfills above the water table in permeable soils and rock may result in more serious ground-water pollution than deposition of the same wastes in an impervious zone below the water table.

8. Finally, location of sanitary landfills in carbonate terranes above or below the water table is likely to cause ground-water pollution. Such pollution can be minimized by proper landfill design, or by provision for collection and treatment of the leachate.

ACKNOWLEDGEMENT

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DISCUSSION

The following questions were answered by Michael Apgar or Dr. Donald Langmuir, after delivering their talk entitled "Ground-Water Pollution Potential of a Landfill Above the Water Table."

Q. *How did you measure the free water table in the refuse cell?*

A. (Apgar) We had a sump drilled into the refuse of the 1967-dated cell that didn't go through the floor of the cell. The water level within this cell was generally 2-5 feet above the floor of the cell depending on the season, so that some of the refuse material was always saturated. The ground-water table was encountered 230 feet beneath the valley bottom.

Q. *If the leachate could be collected, what treatment process would you recommend for it?*

A. (Apgar) It would have to go through some kind of oxidation procedure. Some of the objectionable constituents including high BOD's, high iron, and high ammonia values can be removed by raising pH and dissolved oxygen levels. There's a landfill in southeastern Pennsylvania that has a permit to operate because they agreed to collect and treat their leachate. In some cases one should be able to collect leachate and dispose of it in a municipal sewer system. Dissolved solids and BOD contents are much higher in leachate than in sewage, but leachate would generally constitute a small fraction of the total volume of waste water entering a sewage treatment plant.

Q. *Why not use COD rather than BOD measurements to indicate the extent of organic pollution? Do you consider treatment by dilution to be desirable?*

A. (Apgar) In answer to the first question, this study was initiated before Dr. Langmuir or I became associated with it early in 1969. BOD's were being run on the leachate then. We continued running BOD's so that data subsequently collected would be directly comparable to that collected earlier. Also the Health Department Lab in Harrisburg was set up to do BOD's but not COD's at that time. Certainly, dilution of leachate as a means of treating it is a good idea. If you can dilute anything enough, you can eliminate its objectionable qualities. Dilution of leachate by fresh recharge reduces the cost and need for subsequent treatment of the leachate by natural processes or in a treatment plant. Certainly, one should design a landfill to maximize natural dilution of leachate.

Q. *You stated that disposal in ground water would definitely result in ground-water pollution problems. Just what do you consider the definition of pollution?*

A. (Apgar) Perhaps as good a definition of pollution as any is that a polluted water is one that has picked up constituents resulting from man's activities which render the water unfit for certain uses. Of course this means that a water polluted for one use may not be polluted for some other use.

Q. *What about contamination of your samples of leachate collected from the sampling devices?*

A. (Apgar) Because our soils were unsaturated, we were forced to collect the samples using suction lysimeters. I'm not sure if you're familiar with these or not. A suction lysimeter is a tensiometer, the depth of placement of which is not limited by suction lift. We were able to collect water samples from a depth of 70 feet in unsaturated soil using lysimeters. I have a slide here of a suction lysimeter. The lysimeter is a plastic tube 2 feet long and 2 inches in diameter, with a porous ceramic tip on the bottom which has pores about 1 micron or less in size. It has 2 tubes running down into it which can be evacuated from the surface so that a vacuum exists inside the tube. Soil moisture held under tension in the soil in unsaturated conditions can be pulled through this ceramic tip if the vacuum in the lysimeter exceeds the soil moisture tension. After two weeks or a month, the lysimeter may collect 500 to 750 ml of soil moisture. At this time you untie the tubes at the surface; then with a bicycle pump, you pump air down into the lysimeter forcing the sample to the surface. As far as we are concerned, this procedure minimizes sample contamination problems.

Q. *Do you think Eh measurements of leachate are meaningful? Doesn't oxygen get into the leachate samples and make such measurements useless?*

A. (Langmuir) We have worried about the significance of Eh measurements quite a bit. For an Eh measurement to be meaningful, it must be controlled by a reversible oxidation-reduction reaction. In the iron system there is a reversible reaction between dissolved ferrous iron and suspended ferric oxyhydroxides. A total iron measurement on most leachates gives you the sum of both these forms of iron, although most of the iron present is in the dissolved ferrous form. Assuming the total iron is all ferrous, we can compute an Eh value from the pH and iron analysis which roughly equals the measured Eh, so the thermodynamics seem to work reasonably well in this case and the Eh's seem meaningful. There is considerable ferrous iron dissolved in many freshly-collected samples, and not much oxidation occurs during an Eh measurement in the field, so that such measurements made just after collection are probably fairly reliable.

Q. *What trace metals would you analyze for in leachate?*

A. (Apgar) Although the results were not given in our paper, we had a few emission spec analyses run on the leachate. Apart from iron, which was usually in excess of the potable water limit of 0.3 mg/l, manganese which has a limit of 0.05 mg/l, was as high as 50 mg/l. In a few samples lead and copper were as high or higher than the potable water limits for these elements. A surprising discovery was the presence of up to 1 mg/l each of the rare earths yttrium and ytterbium. The only other refuse materials that come into the landfill besides municipal wastes from surrounding towns and from the university, are from a local television tube manufacturer. Possibly wastes from this latter source are contributing the rare earths.

Q. *When it rains and surface runoff flows in the valley bottom, is the quality of this runoff affected by the landfill?*
A. (Apgar) Yes, as a matter of fact storm runoff from the landfill includes water which has been in contact with the refuse. As the runoff in the stream channel flows through the site during wet weather, its quality progressively worsens. Some contamination of water in the deep well may be occurring by movement of the runoff into sinkholes, although the runoff is less contaminated than ground water from the well.

Q. *You say the deep well is contaminated by the landfill only. Can you exclude possible contamination by the housing development nearby?*
A. (Apgar) We didn't want to overcomplicate the picture during this presentation. We have been limited by budget restrictions to drilling one well. Obviously it is impossible to know anything about the horizontal movement of contaminated ground water when you only have one hole in the ground. Yes, there is a housing development 2000 feet away, and a sewage lagoon about 1500 feet from the well failed in 1969, although the lagoon hasn't operated since then. Based on water levels in other wells in the area at least a quarter or half mile from the landfill well, the general direction of ground-water flow is probably not from the area of the lagoon toward the landfill well. Also, the well water is continuing to deteriorate in quality. We consider this as further evidence that pollution of the well is by landfill leachate and not sewage from the lagoon.

It would certainly be most useful if we could obtain support to drill two or preferably three more wells close to the landfill so as to more exactly establish the character and direction of ground-water flow and extent of leachate contamination of ground water.

Q. *Are your suction samplers similar to those devised by Cole? If not, how do they differ? Also, is there evidence of differential filtration through the porous ceramic cup of the lysimeter?*
A. (Apgar) The lysimeters we used were obtained from the Soil Moisture Equipment Corporation in Santa Barbara, California. I don't know if they are similar to equipment used by Cole. We consider samples collected in the lysimeters representative of the quality of the moisture on the outside. We are dealing with levels of contamination that are so highly different from the quality of the original soil moisture, that whether or not the sampling devices exclude or absorb small amounts of material is not going to make much difference. Naturally, we cannot examine contamination by bacteria or other suspended material in the leachate because these materials are likely to be filtered out by the porous cup. However, such materials would likely be filtered out by the soil anyway.

Q. *Can you give any information on the probable behavior of microbial contaminants and viruses in the leachate?*
A. (Apgar) I can't do that with confidence because, as I just mentioned, such suspended materials are probably filtered out in sampling. We did look for total coliform bacteria in selected leachate samples from the lysimeters, but the tests all proved negative.

Q. *Some of your graphs indicate a marked increase of pollutants with depth in soils below the refuse. How far above the ground-water table should the base of a landfill be to prevent pollution? Could a standard be set?*
A. (Apgar) Such a distance is going to vary from one site to another. You can't say that 30 feet or even 230 feet as in this case, will be sufficient to prevent ground-water contamination by landfill leachate. The safe distance will depend on the local climate, topographic and geologic setting, and the amount and character of soils and of refuse materials.

Ground-Water Pollution and Sanitary Landfills—A Critical Review[a]

by A. E. Zanoni[b]

ABSTRACT

The principal studies concerned with the ground-water pollution potential from sanitary landfills and dump grounds have been conducted in California, South Dakota, Illinois and England. These studies have all demonstrated that leachates are highly pollutional in characteristics, but once they pass into the surrounding soil regime, the attenuation mechanisms of dilution, adsorption and microbial degradation tend to reduce the impact of this loading on the underground-water supply.

A survey of practice in twenty-one States in the United States regarding ground-water pollution from landfill operation showed that not much new research was underway; there was much variation in the code and laws dealing with ground-water pollution; and suggested distances from landfill to water wells varied from 50 to 1000 feet.

Finally, based on the literature findings plus the result of the State survey, a set of recommendations are offered to minimize ground-water pollution problems stemming from landfill operations.

INTRODUCTION

Ground water can be polluted in numerous ways in spite of the protective mantle which nature has provided. Liquid pollutants can originate, for example, from waste water stabilization ponds, sludge lagoons, barnyard runoff, septic tank leaching fields or seepage pits, pit privies and the deep well disposal of certain industrial wastes or treatment plant effluents. Pollutants can also originate from the leachates of decomposing solid wastes as in the case of open dumps, sanitary landfills, solid waste composting sites, industrial refuse, and treatment plant sludges. In the first case the pollutants are already dissolved or conveyed by the liquid stream, whereas in the second case, sufficient water must pass through the decomposing mass to "leach-out" the pollutants and convey them to the ground-water source.

There is no doubt that a large amount of the solid wastes generated in the coming years, or the residues and by-products of solid waste treatment methods presently known or to be developed, will be deposited on the land. Vaughan (1968), in his interpretation of the preliminary findings of the *National Solid Wastes Survey*, stated that the average amount of solid waste collected in the U. S. is over 5.3 pounds per person per day, or more than 190 million tons per year. It is predicted that these values will increase to 8 pounds per person per day and 340 million tons by the year 1980. The amount of waste actually generated is considerably more than noted above, amounting in 1967 to 10 pounds of household, commercial and industrial wastes for every man, woman and child per day, totalling over 360 million tons per year. It is further estimated that the current annual expenditure to handle and dispose of these wastes in this country is $4.5 billion per year.

This paper is concerned with the ground-water pollution potential associated with the operation of dumps, sanitary landfills, and any other practices of the land disposal of solid wastes. The paper first includes a critical review of the important literature covering the area of the ground-water pollution potential from sanitary landfills and dump grounds. This is followed by a review of the practices in 21 States in the U. S. related to this same topic. Based on the information derived from these two sources, a series of recommendations are suggested to a "regulatory agency" concerned with the task of approving and licensing of solid waste disposal sites.

Confusion often exists in a paper of this type as to what is actually meant by a "sanitary landfill." An often quoted definition has been supplied by ASCE (1959) as follows:

> "Sanitary landfill is a method of disposing of refuse on land without creating nuisances or hazards to public health or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation or at such more frequent intervals as may be necessary."

Using the above definition it is apparent that there are many operations involving the land disposal of solid wastes which certainly do not come under the strict egis of a sanitary landfill. This fact has been substantiated by Klee (Vaughan, 1968) who analyzed the data obtained from the *National Solid Wastes Survey* on over 6000 land disposal sites. Using the modest criteria that a sanitary landfill is one in which there is daily cover of refuse, no open burning, and no water pollution problem, it was estimated that only 6 percent of the 6000 can be reasonably characterized as "sanitary landfills." In view of the above it was decided for the purposes of this paper to use the term "sanitary landfill" or simply "landfill" in the very broadest sense. The primary concern was simply what effect land disposal of refuse or solid wastes of any kind, either in the form of a true sanitary landfill or an open dump, has on the ground-water quality in the vicinity of the operation.

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LITERATURE REVIEW

Major Studies

After examining some of the literature in this area, it became readily apparent that certain groups or States had conducted and are still conducting most of the research. Without doubt since the early 1950's there has been more activity in the State of California in this regard than any other State in the country. One of the first studies was an in depth investigation on the leaching of soluble salts and alkalies from incinerator ash dumps (State of Calif., 1952). Following this study, the City of Riverside sanitary landfill was used as the site for the investigating of the leaching properties of a typical municipal refuse (State of Calif., 1954a; Univ. of Calif., 1955; Univ. of Calif., 1956). Two often quoted conclusions from this study regarding the effects of landfills on ground-water quality are:

> 1. "A sanitary landfill, if so located that no portion of it intercepts ground water, will not cause impairment of the ground water for either domestic or irrigational uses."
>
> 2. "A sanitary landfill, if so located as to be in intermittent or continuous contact with ground water, will cause the ground water in the vicinity of the landfill to become grossly polluted and unfit for domestic or irrigational uses."

In 1961 another report was written entitled, *Effects of Refuse Dumps on Ground-Water Quality* with the main purpose of collecting all available data on the extent of pollution of ground water from dump leachates, and to make recommendations for future research programs to fill any gaps in knowledge available (State of Calif., 1961). The report included a good literature review of such topics as vertical water movement, decomposition process, gas production and movement, leaching, and travel of pollution. The concern about gas production in recent years was the impetus for the initiation of another study entitled, *In-situ Investigation of Movements of Gases Produced from Decomposing Refuse* (State of Calif., 1965; State of Calif., 1967; Bishop, Carter and Ludwig, 1966). This study proved to be of interest since up to that time most work had been done on the question of refuse leachates affecting ground-water supplies, whereas, practically no work had been done on refuse-produced gases as potential ground-water pollutants. Merz and coworkers (Merz, 1969) of the University of Southern California conducted a five year study on sanitary landfills using four specially constructed cells at the Spadra Landfill operated by the Los Angeles County Sanitation District. Finally, in 1965, the California Legislature directed that a study be made of water quality problems in the San Francisco Bay-Delta area including water contamination and pollution resulting from disposal of solid wastes. This study resulted in the preparation of a report entitled, *A Study of Solid Wastes Disposal and Their Effect on Water Quality in the San Francisco Bay-Delta Area* (Calif. Water Board, 1968). One chapter in the report entitled, "Influence of Solid Wastes on Water Quality" presents a short review of some of the literature on leachates and gas production from disposal sites. Reference is particularly made to past California studies. Included also is a rather extensive survey of all land disposal sites in the Bay-Delta area from the standpoint of surface and ground-water quality. A water quality evaluation scheme was worked out and applied to each disposal site.

Andersen and Dornbush (1967, 1968) of South Dakota State University have been studying, over a period of almost ten years, the effects on ground-water quality of dumping refuse from the city of Brookings in an abandoned gravel pit located 2 miles south of the community. The ground-water table at the site is about 6½ feet below ground surface and the principal geological feature of the area is a sandy-gravel outwash covered at the surface by about a one foot clay and silt alluvium. The cation exchange capacity of the area was felt to be very low. The estimated ground-water velocities are in the range of 1 to 3 feet per day. Throughout the study period, a total of 45 test wells have been constructed "upstream" and "downstream" of the dump area. After some preliminary studies, they found that chloride, sodium, specific conductance, and total and calcium hardness were the inorganic parameters of ground-water quality which could be used most effectively to denote any changes attributable to leachates from the disposal area. On the basis of statistical studies they found that chloride level is the most sensitive parameter with wells, for example, in the center of the disposal area experiencing a 50 fold increase in concentrations in comparison to the unaffected ground water. Isoconcentration lines drawn for hardness and specific conductance demonstrated clearly that the significant leaching effects of these two parameters on ground-water quality remained in the immediate vicinity of the disposal area. High concentrations of these parameters were confined to a relatively narrow band but extended as far as 1000 feet from the landfill disposal area. The most recent work at the Brookings site has been directed toward an evaluation of the effects of constructing a long trench on the quality of the degraded water flowing from the disposal area. The trench was constructed along the downstream edge of the disposal site. Upon an evaluation of the water quality data above and below the trench, it was concluded that the intercepting trench improved the quality of the degraded ground water flowing from the fill area. It was felt that this beneficial effect was caused by the dilution and photosynthetic activity afforded by the surface water.

A number of studies have also been conducted in England through the years. One often referred to study is called, *Pollution of Water by Tipped Refuse* (Ministry of Housing and Local Govern., 1961) in which the leaching properties of a landfill were compared under "dry" and "wet" conditions. In the case of the former, the refuse was dumped under dry conditions and a known amount of water was applied to the refuse; whereas in the case of the latter, the refuse was dumped into water. Considerably more pollutional matter was leached from the refuse under the wet conditions and during a shorter period of time. The publication also includes some work on the possibility of setting up a landfill site to collect all leachates, direct them to a central point and provide treatment prior to disposal just like any other waste water, and the possibility of removing stabilized refuse from an "ideal" site for the reuse of a fresh refuse. More recently, a symposium was held on "The Effects of Tipped Domestic Refuse on Ground-Water Quality" in which the results of four investigators were reported (Water Treatment and Examination, 1969). None presented evidence of any serious degradation in ground-water quality resulting from the land disposal of solid wastes.

Some of the most useful studies in recent years on landfill site selection and evaluation from the standpoint of practical applicability of the information have been conducted by investigators of the Illinois State Geological Survey. Hughes (1967), for example, wrote a very helpful publication on a methodology for evaluating a disposal site considering the hydrologic environment of the site and the method of disposal. He stressed that climatic, hydrologic, and geologic factors strongly influence the production and spread of contaminants from landfill sites, and therefore it is dangerous to over-generalize the findings from one area to another. Cartwright and McComas (1968) conducted earth resistivity and soil temperature surveys around four sanitary landfills in northeastern Illinois and concluded that,

> "Geophysical surveys are not a substitute for hydrogeologic studies, but can be used with moderate control as a preliminary tool in the investigation of sanitary landfills, and can be extremely useful in the location of piezometers for detail studies."

Bergstrom (1968a, 1968b) discussed the feasibility of disposing of industrial wastes into deep geological formations in the State of Illinois. He (Bergstrom, 1968c) also discussed in general the disposal of wastes of all types in the ground from the broad standpoint of waste management. He stated that instead of viewing waste disposal on land immediately as a ground-water pollution problem, many ground-water workers are beginning to take a more positive role by studying and classifying hydrogeologic environments relative to waste disposal. Cartwright and Sherman (1969) wrote an interesting and very useful document entitled *Evaluating Sanitary Landfill Sites in Illinois* in which they point out, among other things, that limestone quarries and gravel pits are rarely, if ever, acceptable refuse disposal sites from a hydrogeologic standpoint, but that sanitary landfills can be located in relatively impermeable, or slowly permeable, material so that movement of refuse leachate will be retarded. Hughes, Landon and Farvolden (1969) have reported on a study describing the hydrogeologic environments in the vicinity of four existing landfill sites in northeastern Illinois, in order to determine the controls on the movement of the ground water and the solids dissolved in the ground water. The intention was that this information can then be used by regulatory agencies to help determine environments most suitable for near-surface disposal of waste insofar as contamination of ground water and surface water is concerned. The report has a great deal of practical information to aid the reader in this regard.

Remson, Fungaroli and others of the Drexel Institute of Technology, have been involved in studies on ground-water pollution potential of sanitary landfills for several years. Two recent reports were published containing useful information on the design of a laboratory lysimeter for sanitary landfill investigations, and the design of a sanitary landfill field experiment installation (Fungaroli, Steiner and Remson, 1968; Fungaroli, Steiner, Emrich and Remson, 1968). Though both of these publications do not contain any actual operating data and results, they do provide useful hints for anyone interested in instigating an investigation of this type. In another publication (Remson, Fungaroli and Lawrence, 1968) the authors proposed a method of moisture routing first through the soil cover and then through the underlying compacted refuse. Their method was illustrated by its application to a hypothetical landfill.

A series of papers have been published by LeGrand (1964a, 1964b, 1965, 1968) of the U. S. Geological Survey on the general topic of ground-water contamination from various sources. In these papers he presents a point evaluation system for assessing the contamination potential of a waste disposal site, a very basic and informative discussion on the management aspects of ground-water contamination, the use of "malenclaves" for estimating the areal extent of contaminants in the ground, and a methodology of approaching a ground-water monitoring program.

Other Studies

In addition to the groups or States which have been reported above, a number of other studies have been conducted on the general topic of ground-water pollution from sanitary landfills. Qasim and Burchinal (1970a, 1970b) studied the chemical and pollutional characteristics of leachates from different heights of refuse columns containing similar fill materials of approximately the same age, and operating under similar conditions of percolation and leaching. An interesting conclusion from their study was the suggestion that deeper fills pose less of a pollution problem than do the shallow fills simply because the rate of pollution production is greater initially in the case of the latter. Kaufmann (1969a, 1969b) has written a good review on the topic of hydrogeological aspects of the disposal of solid wastes on the ground, in addition to presenting some preliminary findings on his current investigation on the over-all hydrogeology of two sanitary landfills in the Madison, Wisconsin area. Landon (1969), who feels that site selection for final disposal of solid wastes is one of today's most critical solid wastes problems, wrote an interesting paper to show the necessity and application of hydrogeologic knowledge and concepts to the selection of refuse disposal sites. The use of resistivity measurements for economically obtaining hydrogeological information on a potential landfill site and operating landfill sites appears to have merit, according to findings of Page (1968) and Warner (1969). Finally, Hart (1967) reported briefly on a study which has been going on for three years at the West Berlin, Germany landfill to determine the effect of the compaction of refuse upon the water regime within the fill.

General References

There are a number of references which include a general discussion of the relationship between sanitary landfills and ground-water pollution problems. Most of these sources present brief summaries of the studies which have already been presented in this paper, particularly the California studies. Some are fairly complete and helpful while others are quite brief and of limited usefulness regarding the topic at hand. The main point is that by reviewing several of these sources one can obtain a general overview on the ground-water pollution–solid waste disposal relationship.

Cummins (1968) wrote a short review-type report entitled, *Effects of Land Disposal of Solid Wastes on Water Quality.* Most of the important studies are included in the 15 references cited, but very little detail on results is included. Golueke (1968) wrote a 300 page report which includes abstracts and excerpts from the literature on the broad topic of solid waste management. Because of the nature of the topic, it is not surprising that some of the important investigations in the area of ground-water pollution do not appear in this publication. Two of the ASCE–Manuals of Engineering Practice (ASCE, 1959; 1961) include a short discussion on ground-water pollution. The same is true for the APWA book, *Municipal Refuse Disposal* (APWA, 1966). All three of these discussions draw mainly from the California studies. Sorg and Hickman (1968) have written a small semitechnical report for the U. S. Public Health Service entitled, *Sanitary Landfill Facts* which includes some discussion of water pollution problems. A bibliography is added to the end of the report. The U. S. Public Health Service has also made available a number of helpful bibliographies on the topic of sanitary landfills specifically, and refuse collection and disposal in general (Steiner and Kantz, 1968; U. S. Dept. of H.E.W., 1954-1963). The sanitary landfill bibliography was prepared by Steiner and Kantz of Drexel Institute of Technology and covers the literature for the period 1925 to 1968. Finally Weaver (1956) and Black (1965) have briefly discussed the ground-water pollution problems in some of their writings on sanitary landfills.

Health and Nuisance Problems

Considering the tremendous amount of solid wastes which have been deposited on the land, there are still relatively few recorded instances of serious ground-water pollution problems linked to leachates from landfills and dump grounds. No doubt there have been probably many small localized nuisance conditions which have never been reported. There have also been and still are many cases in which impairment of water quality has not been detected because there have been no noticeable deleterious effects traceable to the water being used. A review of some of the health and nuisance problems recorded is presented below. Some of the information on instances reported are quite detailed and very specific; whereas, many others are similar to the following statement taken from a 1953 Joint Study of the HEW Department and APHA entitled, *Refuse Collection and Disposal for the Small Community* (1953): "Landfills should be so located that seepage from them will not cause hazards or nuisances."

Forty years ago, Calvert (1932) reported on the deterioration of a well water caused by the pit disposal of liquor drained from cooked garbage. The well water before and after contamination showed a substantial increase in iron, total hardness, total solids, CO_2 and total organic nitrogen. The University of California (1952) in 1952 conducted field studies on refuse collection and disposal operation in 13 California cities. In the section on public health problems, no mention was made of ground-water pollution problems other than a minor reference that the possibility of ground-water contamination should be considered in selecting a site for landfill disposal of refuse. *Publication No. 24* of the California State Water Pollution Control Board (State of Calif., 1961) includes several pages on the reported experiences from the literature on health and nuisance problems. The ASCE publication *Ground Water Basin Management* (ASCE, 1961) makes reference to potential ground-water pollution problems from disposal of wastes of any kind on the land. A listing of typical industrial wastes together with common characteristics affecting ground water are presented in the document. Anderson (1964) (APWA, 1963) has written on the general topic of the public health aspects of solid waste disposal and includes potential water pollution problems as one of the matters of public health concern. Hanks (1967) in 1967 wrote a very detailed and well referenced report for the Solid Wastes Program of the U.S.P.H.S. on the *Solid Waste-Disease Relationships.* Under the topic of diseases associated with chemical wastes, several references are cited on the pollution of ground water from the leachates of sanitary landfills. A frequently mentioned report on the subject of ground water is one entitled, *Ground Water Contamination* which presents the proceedings of a 1961 symposium (Robert A. Taft San. Engrg. Center, 1961). In the session dealing with specific incidents of contamination of ground water, Weaver discussed the significance of refuse disposal in this regard, using to a great extent data from the California studies of Merz and others. Chapter five of *Sanitary Landfill*, (ASCE, 1959), a publication of ASCE, is entitled "Public Health and Nuisance Considerations," and includes a section on water pollution. Walker (1969) recently wrote a very interesting paper on ground-water pollution in Illinois, and one of the pollution categories he considered was that of garbage disposal. He makes the statement:

> "Serious contamination of the ground-water reservoirs near these dumps (garbage dumps) can readily occur if the bottom of the depressions is below the water table, or if the earth material separating the dump from the aquifer is primarily silt, sand, or other relatively permeable material."

He presented two actual cases of pollution of ground-water supplies traceable to leachates from garbage dumps. As part of the City of Santa Clara demonstration landfill study, Stone and Friedland (1969) conducted a survey of American cities with populations greater than 10,000. They received replies from 120 landfill sites operated by 102 governmental agencies serving a combined population of 17,800,000. Ground pollution problems were reported at 11 of the sites or approximately 9 percent of the total 120 sites. Williams (1969), who discussed the over-all topic of ground-water pollution, claimed that:

> "Sanitary landfill seepage into sand or an overly deep excavation for a lagoon so that shallow subsurface water in the stream alluvium is intercepted, are two of the most common ways of polluting shallow ground-water supplies."

An interesting case of the contamination of a ground-water supply by an industrial waste has been reported (Mpls. Trib., 1968). A large company in the Minneapolis-St. Paul area dumped isopropyl ether in a disposal site for several years before it was realized that the industrial solvent contaminated the aquifer. The company had to spend $600,000 to remedy the situation. Another example of how an industrial waste landfill can affect a public water supply is the case of Kansas City, Missouri, reported by Hopkins and Popalisky (1970).

Two additional interesting publications should be noted at this point, though they are not specifically addressed to the topic of ground-water pollution from refuse decomposition on the land. One of the reports entitled *Investigation of Travel of Pollution* (State of Calif., 1954b) is concerned with the artificial recharge of aquifers with sewage treatment plant effluents, and thus the principal item of concern is the fate of microorganisms, and organic and inorganic chemicals as the liquid passes through the subterranean soil. The report includes a literature review on the subject. The second report entitled *Status of Knowledge of Ground Water Contaminants* (Stanley and Eliassen, 1961) includes a very comprehensive literature search including better than 700 references on the characteristics and status of knowledge on the various contaminants which can be found in ground water. This report can serve as a valuable reference when specific information is desired on the effects of a particular leachate chemical.

DISCUSSION OF THE LITERATURE FINDINGS

After some review of the literature on sanitary landfills, one point becomes clear almost immediately; that is, there are very few case histories of serious or even troublesome contamination of ground water which are directly attributable to the leachates from sanitary landfills. To be sure there may have been many such instances which were simply not reported. Even more probable, there may be many unknown cases currently of people routinely using water impaired in quality somewhat as the result of the land disposal of solid wastes. The writer, for example, has not learned of a single person who has died as the result of ground water being contaminated by a landfill. Considering the number of landfills past and present and the amount and variety of solid wastes generated in our modern technological society, this is a remarkable situation. This statement is not made at the outset of this discussion to belittle the potential for serious harm to many people through this mechanism, nor to cast any aspersions on the fine research which has been and currently is still being done in this area. But, nonetheless, this point is most critical when considering recommendations for future action in this area, since it is this type of statistic which ultimately motivates action in any similar activity. For example, the greatest impetus for improved public water treatment and distribution works at the turn of the century was no doubt the 20 to 30 typhoid deaths per 100,000 population per annum occurring at that time.

This situation attests to the almost miraculous capability of most soils to attenuate the leachates generated from sanitary landfills. From the results of the literature, there is no question that these concentrated leachates are of extremely high pollution strength. There are few industrial waste flows that would match this material and without doubt no responsible governmental agency would tolerate the discharge of a material like this untreated into a surface body of water. There is an important difference in the subterranean regime, however. The soil provides the site for active microbial degradation of the organics which are present in the leachates. The inorganics are adsorbed to the soil surface and many of the more undesirable ions are exchanged for the more desirable ones. The extremely low velocity of the underground-water resource provides the necessary time for these activities to reach a fair degree of stabilization, thus confining most of the degradation processes to the immediate vicinity of the landfill. The soluble end products are attenuated even further by the sheer vastness of the underground-water body by the simple mechanism of dilution. The highly soluble chloride ion provides a useful tracer for the situation described above. In most of the research studies examined, the chloride concentration in the leachate directly below the landfill was always extremely high. The chloride concentration dropped drastically in water samples taken only a short distance from the landfill operation. At distances of several hundred feet the concentration drops down to almost native or background levels.

Unfortunately the described process does not hold true to the same degree for all geological formations, and therein lies the crux of the problem. The above will usually hold true for unconsolidated formations consisting of varying proportions of clay, silt, fine sand and loam with low to medium permeabilities. For unconsolidated materials of coarse sand and gravels with high permeabilities or consolidated materials such as limestone or shale with fissures, faults or fractures of any kind, the protective mechanism breaks down because of one important reason, that is, time. In formations of the latter type there is much less time available for the degradation process to take place within the vicinity of leachate generation because the underground velocities are much higher. Thus partially "treated" and poorly diluted leachates can appear at greater distances from the landfill. The assumption made here is that the ground-water flow is through and away from the landfill site. If all the flow lines are directed toward the site this situation will not necessarily occur and what probably will happen is that the ground water will discharge at the surface somewhere nearby. Such a situation could then have a deleterious effect on the surface supply.

It is convenient to think of a mass of refuse stored in a landfill site as representing a certain mass or quantity of pollutants. Some of the researchers have in fact done just this when they express specific leachate constituents in terms of weight per cubic yard or per ton of deposited refuse. This mass of pollutants will eventually be generated from the landfill, since the processes of weathering and biological degradation always take place. The important variable again is time. In order to speed up the degradation and weathering process, moisture and favorable temperature are necessary. Usually temperature is not a restricting factor even in northern latitudes since the interior of the refuse mass is insulated from the ambient temperature and the degradation process is exothermic in character. Available moisture then becomes the limiting factor. Rapid degradation will occur in a more loosely packed landfill where surface waters are permitted to percolate freely through the refuse. The degradation process can be slowed up considerably by allowing less surface water to pass through the fill. It is virtually impossible to abate completely this activity. Obviously if the degradation process is retarded by restricting passage of water in any way, more time will be allowed for the natural attenuation process to take place beyond the landfill site. A combination of retarded degradation in a geologic formation of ideal attenuation provides the least likelihood of serious ground-water deterioration. Speeding up the degradation process imposes a greater load on the surrounding geologic formation; and if the geologic formation is a poor one, the problem is compounded. Again it must be remembered that the same pollutional mass is involved in both cases.

It is possible to engineer and operate a landfill operation with the intent of minimizing the amount of percolation through the deposited material. Bottom liners of various types, high degree of refuse compaction, shredding, and highly impervious earth covers are examples of what can be done. These measures would, on the other hand, be highly ineffective in situations where the moisture sources originate from below the landfill. There is no question that in areas where wide fluctuations in the ground-water table occur to the point where the refuse becomes repeatedly saturated with water and then drained, the degradation process is intensified to probably its optimum level. If the attenuation capability of the geologic formation surrounding this site is limited, a situation again exists for serious pollution of the ground water.

Some in the field of solid waste disposal argue that a landfill should be designed for optimum degradation and weathering to occur. This means that an ample amount of water should be permitted to percolate through the fill. It also means that the leachates must then be collected in a drain system and treated prior to discharge to a surface water body or possibly back through the fill. After a reasonable degree of stabilization has occurred the leachates will no longer be collected in the drain system but allowed to pass into the surrounding soil. In this way they argue that the degradation process can be controlled as desired and the possibility of future pollution problems is reduced considerably. Some for example argue that huge quantities of stored refuse located in the earth close to large population centers are akin to geologic pollutional "time bombs" which could be very troublesome to future generations. There is no doubt that landfill sites can be engineered to speed up the degradation process and collect and treat the leachate. However, the economics of this arrangement may favor other disposal methods which, relative to traditional landfills, were formerly considered too expensive.

Another point becomes quite apparent after reviewing the literature in this area. Much more geologic, or more specifically, hydrogeologic expertise should be employed prior to the selection of a landfill site. Someone with training in hydrogeology can establish with a fair degree of accuracy upon an examination of the site and often with a limited amount of field testing what the leachate attenuation potential of a site will be and if the cover material will permit a slow or rapid percolation of water into the fill. Too many landfill sites are selected on a purely political, economic or convenience basis with no or little attention given the geology of the site. It is surprising that regulatory agencies have been somewhat lax in this regard, also. The writer is convinced that attention to this matter alone will minimize many future ground-water pollution problems attributed to landfills.

The major threat to ground-water quality in the future will likely be from the land disposal of industrial wastes. Many of these wastes decompose slowly or are nondegradable, which means the protective mechanism of attenuation afforded by the soil is no longer available. Many industrial wastes can impart odor, taste and even toxic problems to ground waters at extremely low concentrations. With advances in technology and the increase in over-all affluence there will undoubtedly be an increase in the amount and complexity of solid industrial wastes produced. Many new compounds will also be synthesized in the future which can pose either acute or chronic threats to the health of future users of ground water. The present trend toward more stringent surface water quality standards will cause some industries to look toward land disposal for the solution to their industrial waste problems. It is important to keep in mind in this regard that much empirical evidence is available to substantiate the generally innocuous effects to humans resulting from the decomposition of ordinary municipal refuse in the ground. On the other hand, practically each new solid industrial waste completely nullifies the dependence on this past evidence as the primary basis for establishing guidelines to dispose of the new material. For this reason alone it is imperative that extreme caution be exercised in the land disposal of all solid industrial wastes in the future.

SURVEY OF STATE PRACTICES

As a means of becoming acquainted with the numerous problems associated with ground-water pollution from disposal of solid wastes, it was decided to conduct a survey of the activities and policies related to this area in 21 of the States in the U. S. The States selected comprise a total present population of approximately 140,000,000 which amounts to 70 percent of the U. S. population. The basis for selection was somewhat arbitrary, but the list was intended to include the larger States, States in the midwestern part of the country and States in which it was known that some activity in this area was taking place. The States included in the survey were: California, Florida, Illinois, Indiana, Iowa, Kansas, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Jersey, New York, North Dakota, Ohio, Oklahoma, Pennsylvania, South Dakota, Texas, Washington and Wisconsin.

Letters were sent in June, 1969 to the regulatory officials in the various States who were known to be familiar with the solid waste practices within their particular State. The letters first explained the reasons for the information requested and specifically solicited comments on the following four questions:

1. Are you aware of any research activities in your State that are concerned with ground-water pollution from sanitary landfill and open dump type of operation?

2. Does your State have published codes or guidelines regarding site selection for sanitary landfills and dump grounds? Do you have regulations pertaining to the operation of such areas?

3. Does your State specify a minimum distance that a water well can be located from a landfill or dump ground?

4. Do you anticipate that your State will be engaged in some aspect of this question in the immediate future, such as writing new or revising old codes, field research programs, etc.?

Upon an examination of the replies received, which varied in detail from "yes" and "no" answers on the original letter mailed to voluminous replies containing complete laws, codes and research reports, it became readily apparent that there has not been a great deal of research activity in the area of ground-water pollution from the land disposal of solid wastes. A little more than half the States queried responded that no research activities of this type were taking place in their own particular State. Probably the most extensive work in the past has been confined to three States, namely, California, Illinois and South Dakota. Most of the recent work which has been published in this area has originated from universities and public and private research agencies within these States. A few other States are beginning to become a little more active in this regard. They are Maryland, Pennsylvania, and Wisconsin. Another interesting observation was that a number of States are beginning to or are making plans to monitor the ground-water quality in the vicinity of landfill sites. It is the writer's opinion that other States will become involved in this activity in the future.

It was also readily apparent that there is much variation in the details given to codes and guidelines pertaining to the selection of landfill sites, particularly with reference to the possible ground-water pollution problems. These range from a few States which do not have any published codes or guidelines to others like California where one of the Water Quality Control Boards recently published a ten page "Statement of Policy" going into numerous details on classification of wastes and disposal sites primarily to guard against the pollution of ground and surface waters. Many of the State regulations merely included broadly worded statements of the type "Sanitary landfill and other solid waste disposal activities shall not pollute the ground waters and surface waters of the State." Of the States queried, California, Illinois, Maryland, Michigan, Minnesota, New York, Ohio and Wisconsin have made the most detailed reference to ground-water pollution potential. On the most part, these States require as a matter of policy, geological data, water table elevations and other hydrological data prior to the approval of landfill sites. Other States may have local health departments which require the same information, but it was not expressed as a matter of State policy. It was also evident that the States with the most stringent regulations in this regard were the ones with the most recently enacted laws.

The policy on landfill to water well distance employed by the States surveyed appeared for the most part to be a very tenuous one. Eight States would not commit themselves to a specific distance, stating in effect that each case was considered individually before a specific distance was set. For the States that gave a value, the distances varied from 50 to 1000 feet with most of the values in the 100 to 500 feet range. Some States indicated that no specific value was used for sanitary landfills, and thus they gave the values used for the location of water wells from any known sources of contamination. Most of the States which established a distance cautioned that the value was only used as a rough guide and it was by no means a rigid one. The tenor of the remarks in this regard was that no one really knows what a "correct" value is and empirical evidence from the past indicates that a particular value was used in the past without any adverse effects. The lack of ground-water monitoring in the vicinity of landfill sites is probably the primary reason for this dilemma.

Very little research activity was being contemplated in the States surveyed in the immediate future. As was noted previously, some ground-water quality monitoring around landfill sites will be conducted in a few of the States. Most of the States, however, will be active in the area of rules and regulations pertaining to solid waste disposal. Many States were either in the process of revision of current laws or have new laws pending. It also appeared that more emphasis will be placed on ground-water pollution problems in the new regulations. There also appeared to be a trend toward more rigid State control of these activities than there had been in the past.

RECOMMENDATIONS TO A REGULATORY AGENCY

A review of the literature on the subject of the relationship between land disposal of solid wastes and ground-water pollution, plus the survey of practice employed by 21 States in this regard, have suggested certain steps that regulatory agencies can take to minimize problems in this area. The term "regulatory agency" in the recommendations to follow pertains to the governmental entity, agency or department which has the primary responsibility of regulating and licensing sanitary landfill operations within the State.

1. The regulatory agency should have available a geologist on its staff, preferably one trained in the area of hydrogeology, to assist in the sanitary landfill site selection processes within the State.

2. The geologist on the staff should begin to accumulate geological data within the State and broadly outline areas considered to be either good or poor potential landfill sites. The activities in the State of Illinois serve as a good example in this regard.

3. The trend should be towards the requirement of more hydrogeologic and hydrologic field data for sites that are questionable for landfill operations. The burden of proof should be placed on the landfill operator or owner. The staff geologist should be given the responsibility of deciding when additional field data are required. It is the opinion of the writer that much useful information can be obtained even with a modest amount of field testing.

4. The regulatory agency should be very cautious when it comes to the approval of the ground disposal of industrial wastes. An up-to-date file should be maintained on various types of industrial wastes, their degradation properties and their effects on the aquatic environment. A literature search should be made periodically on this topic.

5. The use of ground-water monitoring wells should be considered in those cases where some doubt exists as to future effects of a particular landfill operation. This is somewhat akin to requiring that water samples be periodically taken downstream of an effluent discharge to maintain a check on waste water disposal operations.

6. The regulatory agency should follow as its basic policy the concept of trying to slow down the refuse degradation process by minimizing water percolation through the refuse mass. Slowing down degradation provides more time for leachate attenuation. Past experiences have demonstrated that longer times provide the most effective safety measure when it comes to separating sources of ground - water contamination from points of ground-water use.

7. The regulatory agency should not discourage novel methods of collecting and treating refuse leachates for certain installations where proper monitoring and control can be exercised. When considering facilities of this type, an important lesson to be learned from waste water treatment plant operations is that the smaller and the more remote the treatment facility is, the greater the likelihood of poor operation regardless of the original design and the degree of automation.

8. It is virtually impossible to hold to a specified distance between a point of water use such as a well and the site of a sanitary landfill. Tremendous variations in the hydrogeology surrounding each site precludes the establishment of such a published figure. However, lacking any field data

the distance should be as long as possible in order to have the built-in safety factor of greater time as stated previously. Figures of 500 to 1000 feet are not unrealistic if adequate field data are insufficient to prove otherwise.

9. The regulatory agency should encourage the practice of regional or district approaches to solid waste collection and disposal. Economic incentives should be available to provide funds to make area-wide feasibility studies. This approach will reap great benefits in the control of solid waste disposal practices.

10. As a general rule, the regulatory agency should prohibit the use of abandoned rock, gravel or sand quarries as sites for the disposal of refuse of any type. Standing water in such depressions is usually nothing more than a visible direct link to the ground-water supply. The leachate attenuation mechanism under such conditions is completely lost. If extensive hydrogeologic studies demonstrate that the depression is in a discharge ground-water zone it is possible that such a site can be used for landfill disposal. However, nearby future ground-water withdrawals may change the flow network around such a site considerably. The burden of proof plus any remedial safeguards should be placed on the owner of such a site. As a rule, such sites should not be used unless a thorough hydrogeologic study is made.

11. The regulatory agency should support some research work in this area. Some good examples are the studies on existing landfills which have been conducted in California, Illinois and South Dakota.

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DISCUSSION

The following questions were answered by A. E. Zanoni after delivering his talk entitled "Ground-Water Pollution and Sanitary Landfills—A Critical Review."

Q. *These questions pertain to the closing remarks that have to do with new research: What research would you suggest regarding ground-water pollution due to sanitary landfills? Do you feel that we now have sufficient knowledge of the hydrogeology of sanitary landfills to design, operate, and manage solid waste disposal using this method? Also, why no more research activity in the future? Do the States feel we know enough now? This conflicts with your recommendation for new concepts, research, etc.*

A. To answer the first question, I think the studies of the type Illinois is doing right now are certainly in the right direction. Also more studies on the hydrogeology of sites would be in the right direction. I think that with the data available now, we can do a better job if more is known about the hydrogeology of the specific site involved. As far as the degradation of the refuse is concerned, this mechanism is fairly well understood. The big question is what happens to the leachate once it leaves the immediate vicinity of the disposal site. To extrapolate information and data from one site to another is very dangerous. We need to know more of the hydrogeology of the site in question in order to be able to predict more accurately what the progression of the leachate will be and what the impairment in ground-water quality will be at a specified distance from the landfill site. Did I contradict myself?

Q. *Someone thought you said, "We need no more research activity in the future." The question is, "Why no more research activity in the future?"*

A. No, what I said was the survey of States indicates little research activity in this area will be done in future years. My personal feeling is that there should be more. There is no question about that. As for State agencies, there doesn't seem to be much interest in this research area. I feel it is because we have had no long history of troublesome pollutional situations and, quite frankly, this is what we normally respond to. I am certain that people in the political area would be more receptive to research activities if they were hearing of numerous cases of public health and nuisance problems resulting from sanitary landfill leachates. Very candidly, these are the types of things which motivate politicians and others to act.

Q. *Let me take advantage of the moment and ask a question. In any of the literature work, have you found anyone working on such things as trace organics or perhaps carcinogens?*

A. No. I'm not aware of any such work. Trace elements, yes. We have some indication of this from work in Pennsylvania and Brookings. There is very little work on the degree of bacterial travel from landfill sites.

Q. *Couldn't your miracle be explained by the fact that most landfill sites are deliberately located far from habitations?*

A. I think that it is just simply the environment provided by the soil regime. The active sites, the availability of bacterial degradation activity, the combination of moisture and air; it is just an excellent environment for the breakdown and degradation of organics. It is like a good trickling filter in a sense and then beyond that, it's merely a dilution of the inorganics. Most soils provide an excellent site for this active microbial degradation activity, and perhaps, if the permeability is too high, then this attenuation mechanism drops off because the active sites are less available. Under this situation we haven't got as much time for the degradation to take place. Of course, when the leachate starts getting into the rocks and crevices, none of the attenuation mechanism is available. No doubt the distance that landfill sites are placed from habitation helps, but we should not forget that nature does an excellent job of treating these leachates.

Q. *Might one not wish to maximize rather than minimize the rate of refuse degradation if leachate is being collected for treatment?*

A. Absolutely. No question about it.

Q. *This should be the most economical approach if collection of leachate is practiced, correct?*

A. Absolutely. If the design is such that you are going to collect leachate, then you bring it into the treatment plant at maximum rates. In other words, you maximize biological activity in order to save on dollars. This is a treatment cost we are not accustomed to spending for this type of municipal function, and, I would be very skeptical about approving something like this unless it was controlled and regulated properly. We all know of the sophisticated waste water treatment plants built in small towns and 2 weeks after the engineer leaves, the rural policeman operates it once in awhile and the treatment completely breaks down. This is what might happen with this type of installation unless it is monitored properly, so I would never favor this without good control. I would favor the traditional approach with slow degradation because then time is on your side. If you produce these leachates and don't know what to do with them after you produce them, then you have a problem.

Q. *Do you believe that surface water pollution by landfills may often be masked by other kinds of pollution already present so that surface water pollution by landfills may often be undetected?*
A. That is partly true. I have not run across too much data on this. Hughes of Illinois had some data on this situation. He showed colored slides of leachate oozing out of the sides of landfills and then running into streams. There was a case in Kansas City where an industrial waste deposited for many years began leaching into a river supply. Some of this happens and goes undetected. Some of it has happened and has been detected but I haven't run across a great deal of this type of information in the literature.

Q. *Wasn't the California leachate data collected under conditions of forced leaching?*
A. Yes. In one of the studies when the water was added to the refuse bins in an amount equal to precipitation in the area, no leachate was generated so the researchers had to turn on the faucet to get some data. This is the main reason why in southern California there is not generally a leachate problem. There is not sufficient precipitation to generate significant amounts of leachate. Remember, however, that a serious leachate problem can still occur if the ground-water table rises up in the refuse mass. This situation really causes active degradation of organics with subsequent leachate production.

Q. *Can the data that were collected in California be applied to a true sanitary landfill?*
A. No. You have to be very careful in extrapolating some of these data. This is one point, I think, that comes out very clearly from all these studies.

Q. *Will all sanitary landfills produce a leachate?*
A. It depends on the amount of water passing through the refuse. There have been some sites that have remained relatively unaltered for 20 years. But we must always keep in mind that anything organic must degrade eventually. It is just a matter of time. And if you maintain these semi-dry conditions, it may not happen in 2 years but it certainly will happen in 200 years. It has to degrade if it is organic. It's only the rate that is the big variable here.

Q. *What are the moisture holding capabilities of solid waste?*
A. I don't know a number to give you. This would depend very much on the degree of compaction.

Q. *Would you describe how solid waste disposal can be designated to operate at a normal rate of pollution so that solid waste decomposition and resulting leachate production is manageable.*
A. Well, I think with proper hydrogeologic data inputs it is possible to arrive at a fairly reliable idea of the degree of leachate production expected as well as what eventually will happen to the leachate once it gets into the surrounding terrain. I don't think we'll be able to predict accurately the progression of the leachate but at least we'll be able to determine if potentially we are in a problem area. The type of cover material and degree of its compaction are extremely important, for example. Another important item is how we handle the surface water. If you grade most of the surface precipitation away from the landfill site and you have a relatively impervious top layer, you are cutting down the degradation rate to a very minimal extent and the impact of leachate production will be quite minimal. There is no wonder that we have potential water pollution problems after you see how some of these landfill sites are operated. With the type of data Illinois is beginning to put out, we can approach this design a little more rationally than we have in the past. At the present time sufficient funds are not being expended in the process of selecting a suitable site for disposal of refuse. Some government officials think if you spend more than several hundred dollars for this purpose you are being extravagant. It is just not a very popular governmental activity.

Q. *I'm glad you said that because it is very important to the next question, which I think is a gig. What profession, geologist, hydrologist or engineer, is presently best suited to conduct site evaluation and design studies?*
A. I would say a geologist. If I had $100 and had to pick one, I would pick a geologist, or a hydrogeologist. If I could afford it, I would use both because some of the planning, some of the surface soil quantity calculations, the grading, things of this nature, are more in the engineer's bag, but with limited funds I'd stick to a geologist.

Q. *Is there a general tendency to locate landfills in quarries, ravines and valleys that are very important resources of ground-water recharge? If so, would a change in approach help to protect ground water? For example, bailing and stacking the solid waste.*

A. Absolutely. I think there is this trend simply because these areas—just as they are—are totally worthless for any other application, and if you can show someone a restoration plan with these pretty pictures I told you about before, where you can show usable land being developed from some of these sites, it's very attractive to the city fathers and political leaders, particularly from a tax base standpoint. So these sites are looked at first and I agree with the comment that oftentimes these are recharge areas, and you have to be extremely careful about using these sites. I had some experience with one site northwest of Milwaukee that was a gravel deposit site. It was used to mine gravel for about 10 years and I was asked to look at it for possible use as a landfill site and I was convinced that it could be used. After taking 30 to 40 borings we found there was a very thick, dense clay layer underlining the whole area. The site was simply a gravel glacial outwash sitting on top of a very impervious lense of clay. This is an example of a gravel-sandy area that could be used for the land disposal of solid wastes. In contrast to the previous example, deep limestone quarries with standing water are generally very poor landfill sites because this water is usually a direct outcrop of the ground-water supply.

Q. *Do you feel that the Wisconsin Department of Natural Resources will respect your recommendation to hire a geologist?*

A. There has been discussion of obtaining a geologist for assistance in two areas: water wells and refuse disposal. Nothing has been done as of this date. I've talked to some of the people there and they agreed with me but Wisconsin, like all States, is presently going through fiscal problems that demand just about a total moratorium on hiring. In summation, they have not listened to that particular recommendation yet, but I suspect they will. The people I have talked to seem to be favorable to that direction.

Q. *Could you add to your recommendations the desirability of each State establishing ground-water quality standards to add to those established by HEW for surface waters?*

A. That has been talked about a great deal. I've talked to people personally about this. The enforcement and the monitoring of something like this would be awesome now. Maybe in the future we can look in that direction or try this in isolated cases, but the degree of variation in ground-water characteristics from area to area precludes setting up any kind of rigid standards. As you can imagine, monitoring of the water quality would be very expensive. Nonetheless, there are people who feel that this is the direction we have to go. Economically I can't see how we can justify it yet. It's much easier to sample a moving stream than it is to get to a ground-water table 100 feet below the ground surface.

Effect of Early Day Mining Operations on Present Day Water Quality[a]

by Leland L. Mink[b], Roy E. Williams[c], and Alfred T. Wallace[d]

ABSTRACT

Mining operations within the Coeur d'Alene District of northern Idaho have been continuous for over 85 years. Data presented herein demonstrate that early day mining and milling wastes are now affecting the ground-water quality in several locations. One of the affected areas is the lower Canyon Creek Basin located in the Coeur d'Alene District near Wallace, Idaho.

Ground-water pollution of the Canyon Creek Basin results from leaching of old mine tailings that are intermixed with the upper part of the sand and gravel aquifer. High zinc, lead and cadmium concentrations occur in ground water and soil samples taken from the portion of the sand and gravel aquifer containing old mine tailings.

Analysis of water samples from a settling pond located in the upper portion of the study area indicates that the pond water is not the source of the heavy metal concentrations found in the ground water. However, the water from the pond's decanting system provides recharge to ground water and compounds the problem.

INTRODUCTION

Purpose and Scope of Study

Interest in the environment during recent years has focused considerable attention on the quality of several streams in industrialized areas of northern Idaho. Much of the attention is centered around one of Idaho's most important industries (mining). Consequently, researchers at the University of Idaho and the Idaho Bureau of Mines and Geology have established a program under the support of the U. S. Bureau of Mines to collect, analyze, and interpret water quality information so that industries involved would have a basis for corrective measures where needed.

Much of Idaho's mining activity is in the Coeur d'Alene River Basin located in the panhandle region of northern Idaho within the Bitterroot Range of the Northern Rocky Mountains. This paper is concerned with a tributary of the South Fork of the Coeur d'Alene River called Canyon Creek, the scene of mining activity for over 85 years (see Figure 1).

This study was designed to: (1) report on the water quality of Canyon Creek; (2) report on the ground-water quality of the Canyon Creek Basin; and (3) attempt to gain an understanding of the causes and sources of high heavy metal concentrations known to exist within the ground water and surface water of the Canyon Creek Basin. Initially, point number 3 was particularly perplexing because metal concentrations in ground water and surface water are considerably higher than metal concentrations in the effluent from the only significant tailings disposal system in the valley.

DESCRIPTION OF STUDY AREA

Canyon Creek flows in a relatively narrow canyon for approximately 12 miles. Its headwaters are in the Bitterroot Mountains at the Idaho-Montana border; and its mouth is at the confluence with the South Fork of the Coeur d'Alene River at Wallace, Idaho (see Figure 1). Canyon Creek basin has a maximum elevation of 6785 feet and a minimum elevation of 2760 feet, giving a maximum relief of 4025 feet. Many of the slopes of the area are inclined at an angle of 30°; the terrain is very rugged. Most of the Canyon Creek valley is steep and narrow; only one portion of it approaches a width of one-half mile. The entire basin occupies an area of 21 square miles.

The population of the Canyon Creek drainage basin is approximately 250 (Driscall, 1970).

The main industry along Canyon Creek is mining. At present, there is one large operating mine and several smaller working mines in the basin.

BASIN ANALYSIS

Climate

The climate of the Canyon Creek basin is strongly seasonal with mild temperatures prevalent during the summer months and below-zero temperatures common during the winter months.

Most of the precipitation is in the form of

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

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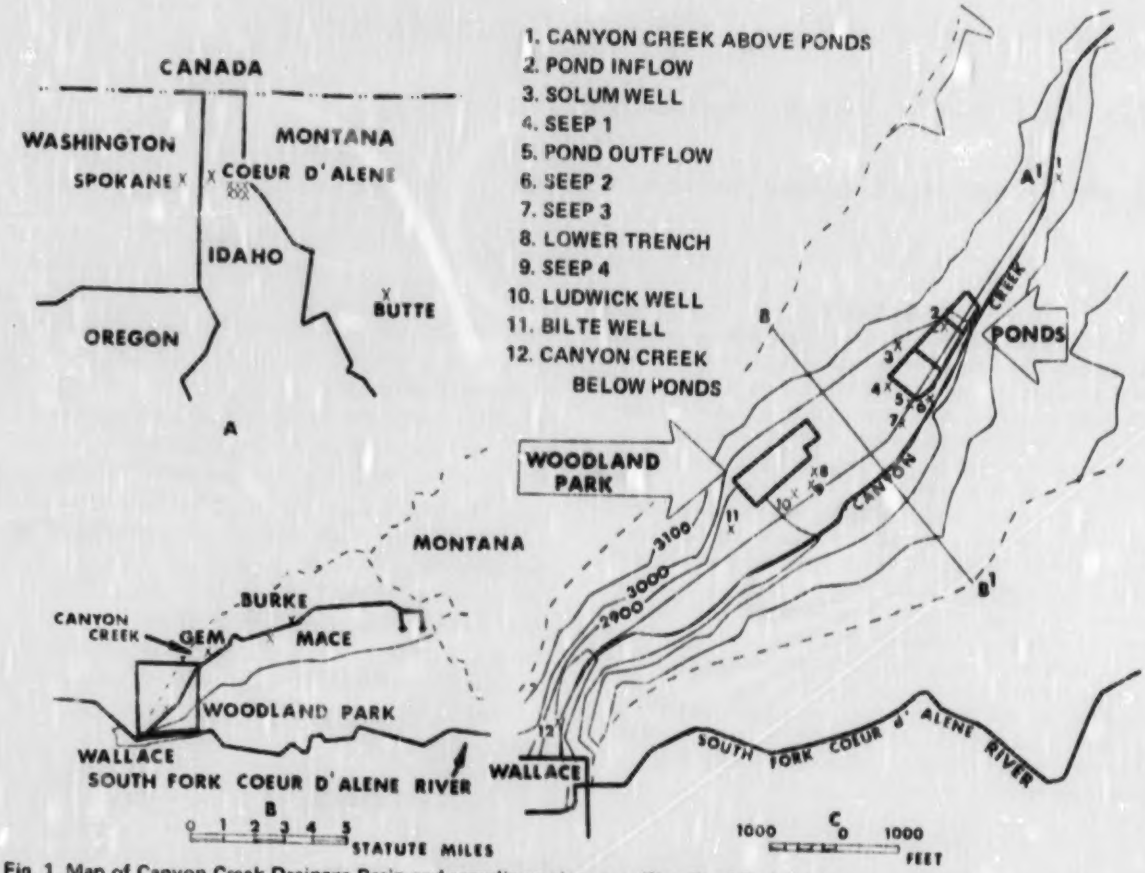
1. CANYON CREEK ABOVE PONDS
2. POND INFLOW
3. SOLUM WELL
4. SEEP 1
5. POND OUTFLOW
6. SEEP 2
7. SEEP 3
8. LOWER TRENCH
9. SEEP 4
10. LUDWICK WELL
11. BILTE WELL
12. CANYON CREEK BELOW PONDS
CANADA
WASHINGTON
MONTANA
SPOKANE
COEUR D'ALENE
IDAHO
BUTTE
OREGON
A
MONTANA
BURKE
CANYON CREEK
GEM
MACE
WOODLAND PARK
WALLACE
SOUTH FORK COEUR D'ALENE RIVER
B
0 1 2 3 4 5
STATUTE MILES
WOODLAND PARK
PONDS
CREEK
CANYON
A'
B
B'
3100
3000
2900
WALLACE
SOUTH FORK COEUR D' ALENE RIVER
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1000 0 1000
FEET

Fig. 1. Map of Canyon Creek Drainage Basin and sampling points near Woodland Park, Idaho.

snow which falls during the winter months. Thundershowers persist from late June through part of August. In the latter part of September and early spring a short rainy season can usually be expected. Snow at higher elevations accumulates in large drifts and, where protected from the sun, may remain until late August. Some deep snows in cirque basins may persist until covered by the next winter's snowfall. Subsurface and surface runoff from these drifts supply runoff to Canyon Creek and other streams throughout the year. The average annual precipitation of the Canyon Creek basin at Woodland Park is 44.7 inches; consequently, ample water is available for recharge of ground water in buried valley aquifers such as that along Canyon Creek.

Geology

The rocks of Canyon Creek basin consist mainly of the Precambrian Belt Series. The rocks are fine-grained argillites and quartzites associated with smaller amounts of carbonate-bearing, dolomitic rocks. Quartz and sericite are the principal minerals within the Belt Series; accessory minerals include feldspar, muscovite, magnetite, ilmenite, zircon, tourmaline, rutile, and titanite. Representative chemical analysis of the Belt Rocks is presented in Table 1.

Table 1. Chemical Analysis of Belt Rocks in Percent of Unaltered Rock in Coeur d'Alene District[1]

Oxides	*Percent*
SiO_2	67.4
Al_2O_3	13.8
Fe_2O_3	2.4
FeO	1.28
MgO	2.78
CaO	2.11
Na_2O	1.76
K_2O	3.6
TiO_2	0.49
P_2O_5	0.12
MnO	0.05
CO_2	2.51
H_2O	1.85
	100.15

[1] From: Hobbs and others, 1965, p.28

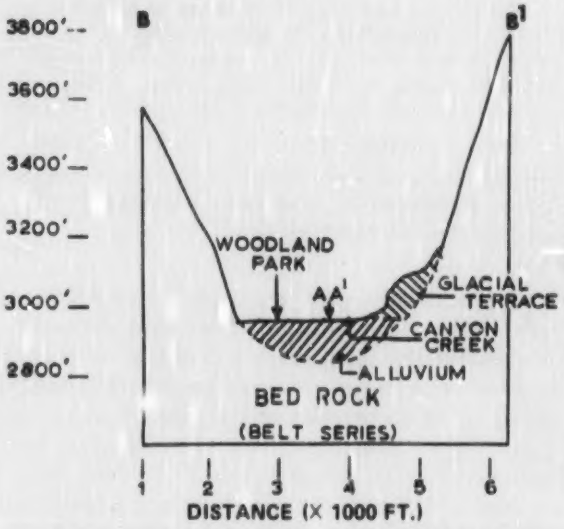

Fig. 2. Cross section B-B^1 of Canyon Creek Basin at Woodland Park showing valley configuration.

The river valleys are partially filled with alluvial deposits which vary in thickness from less than one foot to several hundred feet. Canyon Creek is filled with alluvium to an unknown depth. The alluvium consists mostly of unconsolidated sand and gravel; large rounded boulders are prevalent. Tailings from early mine milling operations are mixed with river gravels within many valley areas. Figure 2 is a cross section (B-B^1 in Figure 1) of the Canyon Creek valley near Woodland Park which shows the configuration of the valley and alluvium.

There is evidence of Pleistocene glaciation at the head of the Canyon Creek basin. Glacial material is scattered throughout the basin (Hobbs and others, 1965, pp. 68-69).

Hydrology

Stream flows within the Canyon Creek basin are extremely variable. High flow occurs during the spring months coincident with snow melt and a rather low flow occurs during the fall when groundwater discharge and melt from remnant drifts are the major source of water. Spring floods caused by rain and melting snow occur.

The water table along Canyon Creek is shallow with springs in evidence throughout the year, but particularly during the spring months. The valley areas of Canyon Creek produce an adequate ground-water supply for domestic use because of the high permeability of the sand and gravel aquifer. However, much of the domestic water supply comes from the convenient springs and creeks in the basin or from adjacent basins because of the poor quality of ground water. Water costs in the valley are relatively high.

PREVIOUS WORK IN AREA

Mink, Williams and Wallace (1971) initiated the first effort at unraveling the pollution problem on Canyon Creek. Prior to that study, speculation had attributed high metal concentrations directly to tailings pond effluent. An increase in zinc, cadmium, and fluoride concentrations were observed in the South Fork of the Coeur d'Alene River downstream from the entry of Canyon Creek. A mean concentration of 3.07 ppm zinc was observed below the confluence of Canyon Creek with the South Fork while upstream portions of the South Fork of the Coeur d'Alene River showed a mean zinc concentration of 0.18 ppm zinc. In short, Canyon Creek adds considerable zinc to the South Fork.

Mink, Williams and Wallace (1971) noted that the concentration of zinc in Canyon Creek was approximately three times that found in the effluent from the settling pond located near Canyon Creek. Springs and seeps analyzed downgradient from the settling pond gave preliminary evidence of an increase in zinc concentration in ground water with distance downgradient from the settling pond.

More recently, soil and sediment samples (much of which consist of old tailings) collected from the Canyon Creek bed and along the sides of the stream have been found to contain up to 6.0 percent lead and 4.4 percent zinc. Copper concentrations of the sediments have a mean value of approximately 430 ppm.

Analyses of plants collected from the Canyon Creek area have shown mean zinc, lead, and copper concentrations of 80 ppm, 60 ppm, and 10 ppm respectively. These values are about four times higher than respective concentrations in plants growing in areas which did not receive tailings in early mining days.

More detailed analysis of the samples of intermixed soils and old mine tailings will be presented in a subsequent paper by Galbraith, Williams, and Siems.

PROBLEM DESCRIPTION

In August, 1968 a series of two settling ponds were established along Canyon Creek near Woodland Park. The mill and mine wastes are piped approximately six miles to these ponds. The valley area where the ponds were established is approximately 2.5 miles long and 0.4 miles wide at its widest point. The ponds are located on the upper portion of this wide valley area (see Figure 9). The lower Canyon Creek valley is filled with extensive alluvial deposits. These are the deposits on which extensive "jig tailings" or coarse mine wastes from early day mining operations have been deposited.

Because of inefficient early recovery practices, much of the "jig tailings" are high in metal content.

Jigging is a mechanical gravity concentration process. It is used to separate heavy grains from light grains. In its simplest form, equipment consisted of a box without a top and with a perforated bottom. A shallow bed of grains was formed by fluctuating water currents. The heavy grains passed to the bottom; intermediate mixtures remained in the middle; and the lightest rose to the top of the bed. Some of these devices were hand-operated or power-driven units in which the jig was moved up and down in the water; others were stationary jigs in which the water was pulsated by plungers or paddles.

The jig tails along Canyon Creek were produced by the concentrators upstream in the canyon from the late 1880's until the late 1920's and early 1930's when it first became economically feasible to recover the zinc.

During the years mentioned, there was no apparent attempt made to recover zinc and it all went to the tailings which display the high values in zinc that occur in the deposits along this valley bottom. Typical tails for this period showed lead assays of 0.90 percent to 1.5+ percent. No assays were performed for zinc in the feed, concentrate, or tails, but the majority of the zinc obviously went with the tails.

Residents of the area below the tailings pond reported a rise in water levels of their wells shortly after the settling ponds were put into use. Because of this observation and the findings reported above, a more thorough study of the basin was clearly needed.

SAMPLING PROCEDURE

Twelve sampling points were established and monitored from June 1969 through April 1970 with major emphasis on the summer months. These dates include only the period after settling ponds were put into operation by the major mining company located in the river basin. During the study no satisfactory sampling point for ground water in the sand and gravel aquifer was found above the ponds. The water table does not "crop out" at the ground surface as it does below the ponds, and no wells are available at an appropriate location. However, the mining company involved collected and had analyzed one sample of ground water intercepted during the construction of one of the tailings ponds. The results of this analysis are presented in Table 2.

The samples collected include both the inflow and outflow from the settling pond. Seepages, springs, and wells were analyzed to give information on the ground-water quality below the pond. All springs and seepages are listed as seepages; however, most such discharge points are actually springs throughout most of the year. Seepage 1 is located at the lower base of the settling pond embankment which is approximately 50 feet thick. Seepage 2 is located 80 feet to the east side of the lower settling pond between the settling pond and Canyon Creek. Seepage 3 is located 350 feet south (downgradient) of the settling ponds and Seepage 4 is located 2300 feet south of the settling ponds. Three wells analyzed within the basin were the Solum Well located 200 feet west of the settling ponds, Ludwick Well located 2450 feet south (downgradient) of the settling ponds and Bilte Well located 3750 feet south of the settling ponds. Samples were also taken from a trench 2100 feet downgradient from the settling pond. Samples of Canyon Creek above and below the settling ponds were analyzed to determine the effect of settling pond effluent and discharging ground water on the stream (see Figure 1). All wells and seepages obtain water from the sand and gravel aquifer occupying the valley.

Table 2. Concentrations of Metals in Ground Water Above Tailings Ponds[1] (in ppm)

Sample No.	*Copper*	*Lead*	*Zinc*	*Iron*	*Manganese*
SP-1	0.008	0.137	5.96	0.067	0.180

[1] Data contributed by mining company owning tailings ponds; only one sample available.

DATA ANALYSIS

The samples were collected in one-liter polyethylene bottles which were washed in a dilute HCl solution and then rinsed with deionized, distilled water prior to sample collection. The sample bottles were rinsed thoroughly with the sample water at the time of collection. Immediately after collection the samples were analyzed for temperature, pH, and electrical conductivity.

The samples were then analyzed for arsenic (As), calcium (Ca), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn), sodium (Na), nickel (Ni), lead (Pb), and zinc (Zn) using a Perkin-Elmer model 303 atomic absorption spectrophotometer.

Acidification of Samples Containing Iron, Lead and Zinc

Experimentation with acidified and unacidified samples prior to analysis for lead and zinc revealed that acidification increased the concentrations of both ions. Two explanations are possible: acidification is known to minimize adsorption of these ions onto the walls of the container; however, experimentation revealed that acidification also strips off ions adsorbed to the solids suspended in the samples, especially when those suspended solids are mine tailings. All samples analyzed during this project were collected in polyethylene bottles; consequently, adsorption of ions onto container walls would be expected to be minimal. Therefore, the high concentrations of lead and zinc observed in acidified samples are interpreted as being caused by removal of ions from suspended matter in the sample. Filtering of samples was avoided because of the fear of the adsorption of heavy metals onto the filter paper.

If the suspended solids settle out in the natural environment (as in stream channel deposits) the ions adsorbed thereon may never become available to aquatic life. On this basis, and because of the above complications, the decision was made to utilize unacidified samples for analysis. The suspended solids were allowed to settle and the supernatant was analyzed. Inherent in this approach is the assumption that the partition of ionic species between water and solid was at equilibrium. The data represented herein are believed to be as representative as possible of ion concentrations actually in the water, rather than a combination of ions in the water and ions added to, or removed from, the water by a change in the physical-chemical environment within the sample after collection.

Finally, extraction techniques were not utilized in this study. Such techniques are frequently used to lower the detectability limit of dissolved ions by the atomic absorption spectrophotometer. However, it was observed that results were difficult to reproduce when this technique was employed so the decision was made to settle for slightly higher limits of detectability.

WATER QUALITY

Because of the toxic nature of several elements in high concentration, notably cadmium, copper, lead, and zinc, emphasis has been placed on these elements. The area is nationally famous for its silver, lead and zinc production, with copper and cadmium being important by-products from the mining operations.

Interviews with residents of the Woodland Park area indicated that water levels in wells have risen since the installation of the tailings ponds by the mining industry. Inspection of the valley downgradient from the settling ponds revealed that septic tanks and water meters are under water during a portion of the year. Preliminary analysis of the ponds revealed that the ponds were not directly contributing the high zinc concentrations found in Canyon Creek. The pond water contains a zinc concentration of approximately 1.4 ppm while Canyon Creek has a concentration of approximately 4.8 ppm zinc (Mink, Williams and Wallace, 1971). Since this preliminary study the outflow from the tailings pond decant system has been sampled. This water has a mean value of 1.1 ppm zinc (based on 5 samples) which is slightly lower than that found in water within the pond. The seepages analyzed from the basin's sand and gravel aquifer show a high zinc concentration in ground water a considerable distance from the ponds (see Figure 3).

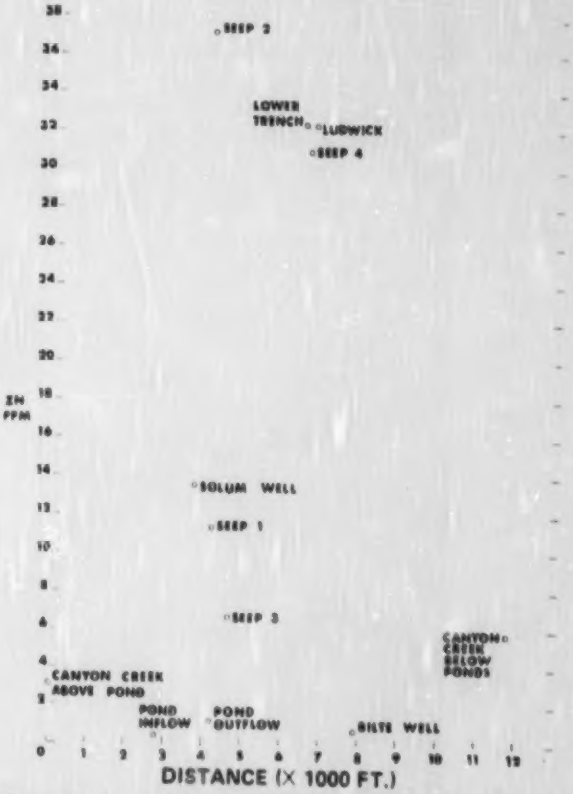

Fig. 3. Graph of mean zinc concentration vs. distance for Canyon Creek Basin near Woodland Park, Idaho (1969-1970).

Samples from seepage 2, seepage 4, lower trench, and Ludwick Well are significantly higher than the rest of the samples in zinc concentration. These concentrations range from a mean of 31.0 ppm zinc for seepage 4 to 37.2 ppm zinc for seepage 2. Solum Well, which is located about 200 feet west of the final (lower) pond, displays a mean zinc concentration of 13.6 ppm. It is not possible to determine whether this relatively high concentration is related to recharge from the tailings pond system. We suspect (but cannot prove) that it reflects ground water which has moved through old tailings above the pond system; the limited available analyses of this water are presented in Table 2. Bilte Well, located downgradient from the settling ponds, had a mean zinc concentration of 0.6 ppm which can be interpreted to mean that ground water in the lower portion of the basin is recharged in a direction perpendicular to the axis of the valley (see Figure 2).

The zinc, lead and cadmium concentrations in ground water not associated with old mine tailings in the Coeur d'Alene basin is < .1 ppm (Mink, Williams and Wallace, 1971). Additional data collected since that study support this conclusion. Based on 14 samples, an increase in zinc concentration was found in Canyon Creek when mean concentrations from samples above the settling ponds were compared to mean values below. Mean zinc concentration in Canyon Creek above the ponds (4 samples) was 3.1 ppm while below the settling ponds mean zinc concentration (14 samples) was 5.9 ppm.

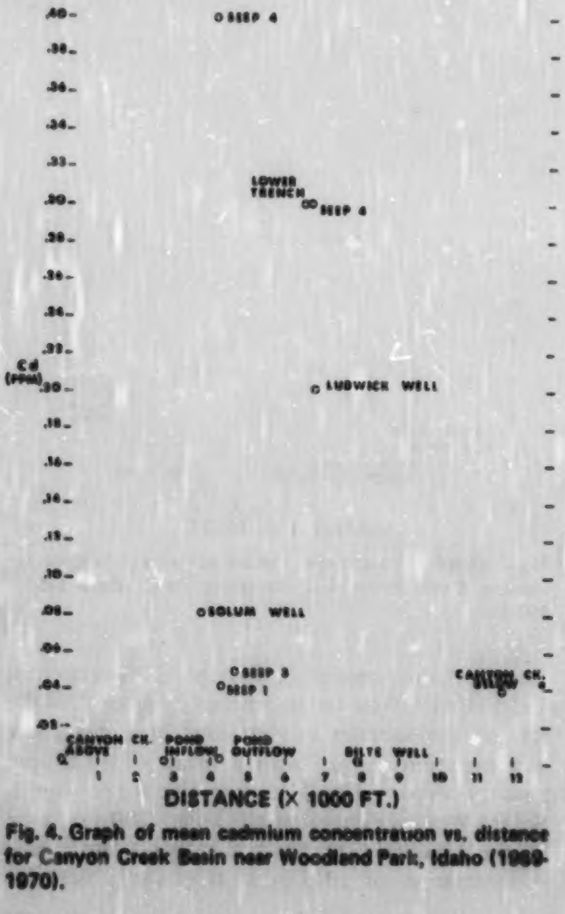

Fig. 4. Graph of mean cadmium concentration vs. distance for Canyon Creek Basin near Woodland Park, Idaho (1969-1970).

Cadmium concentration follows much the same trend as zinc concentration (see Figure 4). Mean cadmium concentrations ranged from 0.40 ppm to 0.20 ppm for seepage 2, seepage 4, lower trench, and Ludwick Well. Cadmium concentrations were below the detectable limit of 0.02 ppm for Canyon Creek above the settling ponds, while a mean cadmium concentration of 0.04 ppm was observed in Canyon Creek 7800 feet below the settling ponds at the lower end of the valley. The inflow and outflow of the settling ponds was always below the detectable limit of 0.02 ppm cadmium.

Lead concentrations are also higher in the seepages than in the inflow or outflow of the settling ponds. Except for 0.1 ppm lead observed in one sample from Ludwick Well, no detectable lead (detectable limit of 0.1 ppm) was found in Canyon Creek, any of the wells, or in the settling pond outflow. Mean lead concentrations (13 samples) in seepage 1, seepage 2, seepage 3, seepage 4, and the lower trench range from 0.6 ppm to 1.6 ppm lead (see Figure 5).

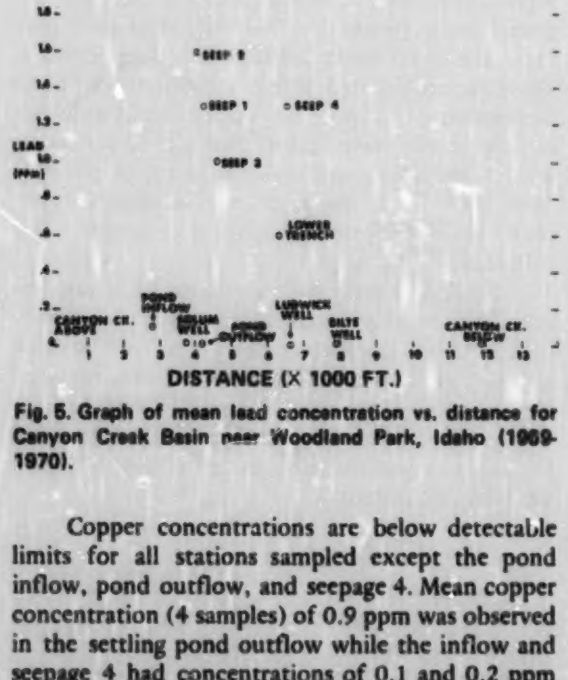

Fig. 5. Graph of mean lead concentration vs. distance for Canyon Creek Basin near Woodland Park, Idaho (1969-1970).

Copper concentrations are below detectable limits for all stations sampled except the pond inflow, pond outflow, and seepage 4. Mean copper concentration (4 samples) of 0.9 ppm was observed in the settling pond outflow while the inflow and seepage 4 had concentrations of 0.1 and 0.2 ppm copper respectively (12 samples). (See Figure 6.)

Values of pH are correlatable with high zinc, cadmium, and lead concentrations. A decrease in pH of ground water occur with distance downgradient from the settling ponds (see Figure 7). The settling pond outflow has a 15-sample mean pH value of 7.40 while the water from seepage 1, has a significantly lower pH of 5.60. The pH of the ground water decreases to a mean value of 4.27 at seepage 4 located 2300 feet downgradient from the settling pond. The pH of Bilte Well is higher than the other ground-water samples, presumably because of recharge of uncontaminated ground water entering the aquifer near the valley sides.

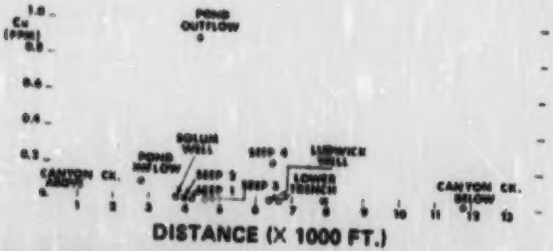

Fig. 6. Graph of mean copper concentration vs. distance for Canyon Creek Basin near Woodland Park, Idaho (1969-1970).

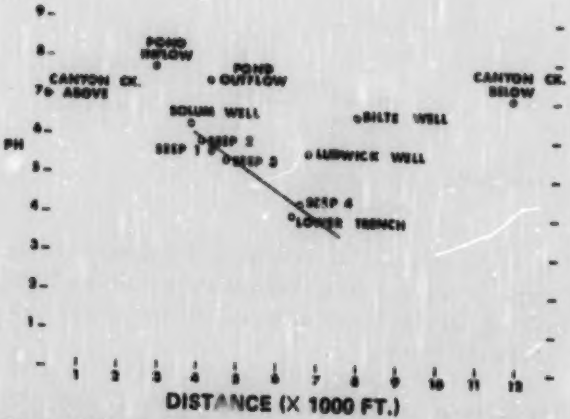

Fig. 7. Graph of pH vs. distance for Canyon Creek Basin near Woodland Park, Idaho (1969-1970).

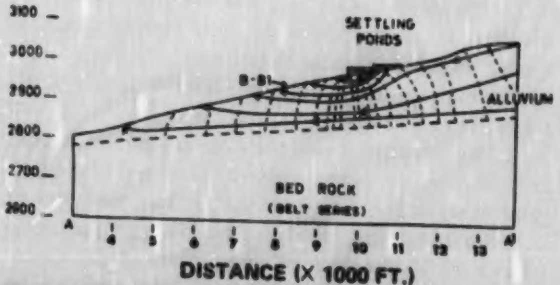

Fig. 8. Longitudinal cross section (A-A') of Canyon Creek Basin near Woodland Park showing proposed flow system.

GROUND-WATER FLOW

Figure 8 shows a longitudinal cross section (A-A') of Canyon Creek with a proposed flow system which is influenced by recharge from settling ponds. The depth of the aquifer is estimated because of lack of data on depth of the alluvium in the valley.

Before the establishment of the settling ponds, it is believed the major discharge area was at the lower end of the valley where the valley narrows and the alluvium thins out. The proposed flow system shown in Figure 8 indicates that a discharge area exists from a point directly below the settling pond to the lower end of the valley. Evidence for this conclusion consists of several springs which now emerge between the ponds and the downgradient end of the valley even during dry weather. The discharge area below the settling ponds brings ground water into contact with the upper portion of the sand and gravel aquifer containing the jig tailings. Virtually all ground water discharges into Canyon Creek before leaving the valley because thickness of the sand and gravel aquifer thins to zero in a narrow constriction above the confluence of Canyon Creek and the South Fork of the Coeur d'Alene River. A water table map of the Woodland Park area shows the water table is near the surface throughout the valley (see Figure 9).

DISCUSSION AND RECOMMENDATIONS

The data presented herein indicate a ground-water pollution problem with respect to low pH and high concentrations of cadmium, copper, lead, and zinc in the sand and gravel aquifer of Canyon Creek. The concentrations of cadmium, lead and zinc are in some cases above the limits set for domestic water supply by the U. S. Public Health Service. The concentrations observed would also be detrimental to many aquatic organisms. Concentrations of cadmium, copper, lead, and zinc found in Canyon Creek below the settling ponds are well above that reported toxic to trout and other forms of aquatic life (McKee and Wolf, 1963, pp. 149, 169, 209, and 294). Of the four elements above, only copper (which is not particularly high) appears to be derived directly from the tailings ponds within the basin. Cadmium, lead, and zinc show a much higher concentration in the ground-water samples than that observed in samples from the tailings ponds. The high concentrations of lead and zinc in soil samples, along with the high concentration of these elements in ground water in the sand and gravel aquifer above and below the ponds in the valley, indicate that the source of metals is within the aquifer located below the water table.

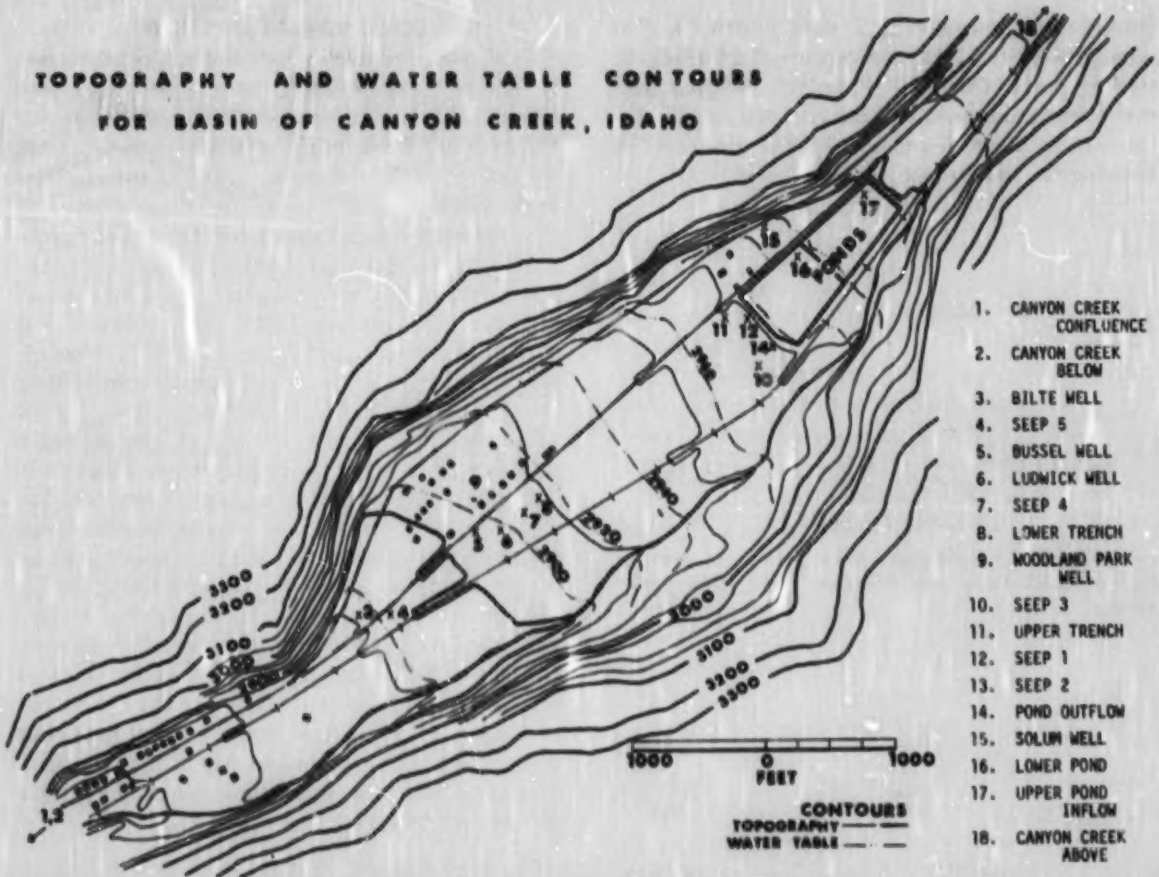
TOPOGRAPHY AND WATER TABLE CONTOURS
FOR BASIN OF CANYON CREEK, IDAHO
3300
3200
3100
3000
3000
3100
3200
3300
PONDS
1000 0 1000
FEET
CONTOURS
TOPOGRAPHY
WATER TABLE
1. CANYON CREEK CONFLUENCE
2. CANYON CREEK BELOW
3. BILTE WELL
4. SEEP 5
5. BUSSEL WELL
6. LUDWICK WELL
7. SEEP 4
8. LOWER TRENCH
9. WOODLAND PARK WELL
10. SEEP 3
11. UPPER TRENCH
12. SEEP 1
13. SEEP 2
14. POND OUTFLOW
15. SOLUM WELL
16. LOWER POND
17. UPPER POND INFLOW
18. CANYON CREEK ABOVE

Fig. 9. Topography and water table contours for basin of Canyon Creek, Idaho.

Essentially all of the ground water moving through the aquifer discharges into Canyon Creek before it enters the South Fork of the Coeur d'Alene River because the thickness of the sand and gravel aquifer diminishes to zero in a narrow constriction immediately upstream from the South Fork.

The decrease in pH of the ground water downgradient indicates that a mechanism is present which solubilizes the metal sulfides of old mine tailings. The sulfide ion then becomes oxidized to sulfate ion. This reaction creates sulfuric acid which accounts for the increase in H^+ ion concentration and the decrease in pH. The H^+ ions can then undergo cation exchange to allow the metal to go into solution. This process, along with an evaluation of the role played by microorganisms, will be discussed in greater detail in a subsequent paper by Galbraith, Williams and Siems. This proposed mechanism could account for the anomalous pH values and metal concentrations observed in the ground water of the Canyon Creek basin. Recharge caused by the establishment of the settling ponds has apparently raised the water table of the valley into the mixture of tailings and sediments. This rise has resulted in additional metal sulfides from old jig tailings being subjected to the mechanism described above.

Trenches from three to fourteen feet deep have been constructed by the mining company concerned and have alleviated the problem to some extent by lowering the water table approximately one to four feet. This drop eliminated some of the seepages in the valley.

To minimize the problem, it is believed that discharge of the settling pond effluent should be diverted from the unlined ditch (upper ditch in Figure 9) where it now flows, to Canyon Creek, a distance of approximately 400 feet. A similar result might be realized by lining the ditch.

The seepage from the settling ponds should be evaluated from the point of view of recharge of ground water by the ponds. At present, the amount of recharge being contributed by this source is unknown. Experience in other parts of the Coeur d'Alene valley has shown that a peripheral tailings discharge system minimizes seepage. The slimes from the milling operation are relatively effective in sealing the ponds. An appropriate technique is described by Kealy and Busch (1971) and Kealy and Soderberg (1969).

Deep trenches constructed at an angle across the valley and discharging into Canyon Creek would further lower the water table below the old mine tailings (jig tailings) and also help solve the problem.

Immediate measures needed include ascertaining that the ground water emanating from the springs and seeps in the lower part of the valley is not consumed by animals or humans. The concentrations of lead observed constitute the primary reason for this recommendation. It is also advisable that the ground water along a band downgradient from the ponds not be consumed.

It must be noted that it is not possible to say with certainty that elimination of recharge of ground water by the tailings pond system will completely eliminate the pollution of ground water. It is apparent that the critical factor is whether or not the old jig tailings in the upper portion of the sand and gravel are saturated. On the basis of testimony by area residents, the pond discharge has raised the water table considerably; however, it is not certain that the water table did not periodically extend up into the layer of old tailings prior to the installation of the tailings ponds. No data are available under original conditions on which to base an opinion. However, it is certain that the tailings pond effluent is contributing to the problem.

In addition to providing an explanation for the heavy metal ion concentrations observed in ground water in the sand and gravel aquifer of Canyon Creek, and in addition to accounting for the heavy metal concentrations in Canyon Creek, this study has demonstrated the need for thoroughly evaluating all aspects of a waste disposal site prior to its use. Had the conditions in Canyon Creek been understood in advance of pond construction, the portion of the problem attributed to the ponds could have been essentially eliminated by one of several design procedures. The industry has now adopted a process of careful site evaluation prior to use, including sampling of initial water quality. This procedure not only facilitates proper design; it also enables the company or other entity involved to specify precisely what effect its operation has had on the environment in the event that any post-installation problems arise.

SUMMARY

1. The Canyon Creek basin has been the location of mining activities for over 85 years. Prior to 1968, most of the waste generated by concentrating plants associated with these operations was discharged into Canyon Creek. This study includes the period of time after the installation of tailings ponds to improve water quality. The study was designed to evaluate and explain the heavy metal concentrations known to occur in the ground water and surface water of Canyon Creek basin.

2. Water samples were collected from 12 stations within the Canyon Creek basin during a period from June 1969 through April 1971 and analyzed for 13 metals along with electrical conductivity, pH, and temperature.

The analyses showed that the concentrations of the elements zinc and cadmium are high in ground water and surface water. Lead is high in ground water discharging at some locations. Lead, zinc, and cadmium concentrations are lower in tailings pond effluent than in surface water or ground water. Zinc and cadmium increase in Canyon Creek as ground water which has moved through the valley's sand and gravel aquifer discharges into Canyon where the aquifer thickness diminishes to zero in the stream channel.

Soils were sampled in an effort to obtain an estimate of the amount of heavy metals contributed to the upper portion of the basin's sand and gravel aquifer by the emplacement of a layer of old "jig" tailings during the early days of mining in the basin. The data indicate that the upper portion of the aquifer contains up to 6.0 percent lead and up to 4.4 percent zinc.

3. The settling pond, established on the upper end of an extensive sand and gravel alluvial deposit which contains old mine tailings, is acting as a recharge area for the basin aquifer and has apparently resulted in a rise of the water table within the basin below the settling pond. This rise has contributed to the raising of the water table into old mine tailings deposited during early mining days. When saturated, these tailings become subject to lixiviation by ground water.

4. The ground-water quality of the lower portion of Canyon Creek is the direct result of leaching of the old mine tailings (jig tailings) which have been deposited by the past mining operations. As a result of this process, high concentrations of cadmium, lead, and zinc occur in the ground water. The process also results in a lowering of pH with distance away from the settling ponds.

5. Solution of the problem can be accomplished by utilization of different design techniques for tailings ponds in this type of environment. Methods described by Kealy and Soderberg (1969)

and Kealy and Busch (1971) should prove successful.

6. It is not possible to determine what the natural conditions were because no data are available. The water table may occasionally rise into the layer of old tailings even under natural conditions. It is certain, however, that the ground-water recharge contributed by the tailings pond effluent intensifies the problem.

7. This study emphasizes the advisability of thoroughly evaluating an area before disposal of wastes is initiated. Without such an examination it is difficult to accurately delineate the role played (or not played) by the waste disposal facility.

ACKNOWLEDGMENTS

The writers are grateful to Mr. Gordon Graig and Mr. William McKee, Hecla Mining Company, Wallace, Idaho for their assistance in investigating the ground-water problems in the vicinity of Canyon Creek. This project was supported by U. S. Bureau of Mines Contract No. H0110088, which is directed at determining what types of wastes tailings ponds can be expected to treat adequately.

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DISCUSSION

The following question was answered by Leland L. Mink after delivering his talk entitled "Effect of Early Day Mining Operations on Present Day Water Quality" (coauthored by Roy E. Williams and Alfred T. Wallace).

Q. *Isn't the significance level of lead and cadmium in water much less than your lowest detectable limit of 0.1 ppm, .005 ppm Public Health Service upper limit? Does this affect your conclusions? Perhaps the problem may be even worse than stated.*

A. This can be true. Our detectable limit is quite high and again we're hoping to improve this situation with our new equipment. Now it is possible that when we receive the results of a few samples we have sent out, the concentrations of some of these elements, for instance, lead, may prove to be present in concentrations which are above the Public Health Service limits but still below our detectable limits. We may have to revise some of our ideas concerning what is polluted and what is not polluted within the basin at that time. However, our objective in this study was to unravel the ground-water pollution problem with respect to sources and causes. We did not set out to monitor exclusively for compliance with standards. Our data did enable us to meet our objective.

Bull Session 3—Solid Waste—Its Ground-Water Pollution Potential

Session Chairman: Jack W. Keeley, Chief, National Ground Water Research Program, Environmental Protection Agency, Robert S. Kerr Water Research Center, P. O. Box 1198, Ada, Oklahoma 74820.

Jack W. Keeley, Lead Bull:

Dr. Zanoni will not be able to be with us. The subject is solid waste and landfill. By recognition, get up to the microphone and ask your question, and we will discuss it; hopefully, we'll get a little controversy going. I hope we can make the thing a two-way discussion. Who wants to be first? Does anyone want to start with anything in particular?

Jack Hennessy, Brookhaven Natural Lanoratory, Upton, New York:

I asked this question earlier today of Mr. Apgar; I didn't feel it was completely answered. If you collected the leachate from the cells, would you describe what treatment methods you would use to neutralize it or to make the leachate non-polluting so it could be discarded?

Michael Apgar, Roy F. Weston, Inc., West Chester, Pennsylvania:

I'm not sure that this is my field of expertise, but the materials in the leachate include organics which have to be oxidized and this could be done by aeration and raising the pH. So, lime treatment and spraying or something like that ought to be able to help it. Then you've got high salt content, and I'm not exactly sure what you could do about that except dilute it—that is why I suggested that an acceptable way to get rid of this stuff might be to put it into a municipal sewer system. I'm not sure if that is being done anywhere right now, but a lot of people have been talking about it. I know that there are at least one and probably two sites; but, I know of one in operation in Bucks County, Pennsylvania, where leachate is collected and treated. But this is a very expensive process because you're not through treating the leachate when you are through utilizing the site for waste disposal. That is, once you're done putting refuse somewhere and you've got a leachate collection and treatment system, you've got to keep operating that treatment system.

The regulations in Pennsylvania have now been made stiff enough so that in some parts of the State permits won't be granted to operate a disposal site unless you go to collection and treatment. So, as far as I know these two operations in the southeastern part of the State of Pennsylvania are the only two that are operating legally now.

Jack Hennessy:

Could you mention any areas that are actually collecting leachate and treating it?

Michael Apgar:

Yes, the Warner Co. is the name of one in Bucks County, Pa.; I have the address somewhere but I haven't visited their site myself.

Russell Stein, Ohio Division of Water, Columbus:

We are just getting into landfill monitoring in Ohio, but I know of one case up near Cleveland, a suburban area, a town known as Painesville up on Lake Erie, where they are collecting leachate from a landfill through underdrains which is going into a sanitary sewer and being treated by the City of Cleveland Treatment Plant. Other than that, there is another landfill in one of the counties in Ohio in which they collect leachate and simply retain it in an oxidation pond before it bleeds out into the nearby stream, which does a little bit of good, but not very much.

I think one of our problems is this idea of whose responsibility it is to treat a leachate. You always have this inevitable time lag in a landfill, particularly a small county landfill, where you may have four or five years of active use in this landfill. Five years after that you may have a leachate problem develop and in the meantime the landfill is closed up. Who is impelled to go back and build a treatment plant? Or better still, if treatment exists, and the landfill operator is operating the treatment plant, what happens to the treatment plant and what happens to the leachate when they finish the landfill operation?

Michael Apgar:

Well, I don't think anybody has reached the point where they have stopped operating a landfill that is operating with a treatment system now.

Russell Stein:

I could give you an example of this. Here in Ohio we are faced with one situation where we have a landfill up near Cleveland which has a really nasty leachate problem. It is not causing any particular ground-water problem because it is in an area served by city water, but it's causing a very bad stream pollution problem. Now, all of the local residents in this area are trying to get an injunction against the operator to shut this down. The State people are trying to impel this landfill operator to collect and treat the leachate. But our feeling is this, if they get an injunction against this man and permanently close this landfill down, there is just nobody available to go in there later and try to correct a very serious pollution problem, unless it would be the State.

Michael Apgar:

This is why in a lot of cases the State might have the authority to do something about a particular site. I know this is the case in Pennsylvania, but they are reluctant to close the operation down because either a private contractor or the municipality itself is running the landfill and by closing them down, even if it is not being properly operated, the operator just moves to another site and the area that was a problem remains a problem. Everybody has moved away and it just sits there and it is a sewer.

Roy Williams, University of Idaho, Moscow:

We have an easy way to solve the problem in Idaho. The operator in one case, or the only case that has come to court was simply given an order by the judge to do a number of things before he left the site; and if he didn't do that, he would be in contempt of court. It took care of the matter.

Michael Apgar:

Yes, but in a lot of these situations it is an expensive proposition to correct any damage or potential damage that's already built into the site. And you can't very well tell a small operator to either dig up the refuse or collect the leachate and treat it or something like that. And in some cases, I think there is another way of getting at this, and that is to shift responsibility back to the people that generated the leachate in the first place.

Is anybody here from Illinois? I understood somebody to say that the liability could be traced back to the people that were putting the material into the site if it could be proven it was their material, even though they said goodbye to it when they gave it to a private contractor or to the local municipal hauler at their generation point and let him take it somewhere. I'm not sure if that's true but that is what I heard.

Jack W. Keeley:

What is objectionable about having built into a contract at the outset that these matters be taken care of [illegible] whatever means is appropriate?

Michael Apgar:

That's a good idea, but I don't think most States are to that point yet.

Warren Hofstra, U. S. Geological Survey, Denver, Colorado:

One thing that occurs to me is that if a State or even a Federal agency is in the position of giving a permit, they can make certain requirements on a thing that has a relatively limited life, say a landfill that will only last 10 or 15 years. It seems to me it would be in order for the governing body to require piping the leachate to a permanent facility, such as a municipal sewer. And, if the site was finally filled or finally used, it would seem reasonable to me that the governing agency—in this case the city or the State, or whoever had it would at that time take over maintenance of the thing as a public health hazard. The other thing would be not to allow any of these things unless they were run by a municipality.

Jack W. Keeley:

Perhaps we are talking about three separate problems. When a landfill is in existence, the permit to construct this facility was based on certain existing local or State legislations. If we get worried about the things and the State or the community passes legislation with a measure of control, we are dealing with private or municipal enterprises, which I think legally are probably a little different. If it is a municipal enterprise, the State agency can simply say cease and desist. If it is a private individual, the operator, probably a corporation if he had any sense, could take bankruptcy, you see. Then who is responsible? Now these are questions that are pretty well established over the country. These then would fall back on the State or the municipality. Can you pass an ex post facto law when dealing with private enterprise? I don't think you can. The State can issue a cease and desist order but the operator can take bankruptcy. Is he then responsible? My point is to open up or maybe guide this discussion along these lines. Does anyone have any comment on the legality?

Roy Williams:

The bankruptcy part is obviously not in the realm of what I was talking about earlier, but let's say that a municipality in Idaho contracts the operation of a landfill to an individual and he isn't bankrupt. I can't see where there would be any problem with writing any restrictions on the condition he must leave the site in when he finishes.

Jack W. Keeley:

You're talking about before the fact though.

Roy Williams:

Yes, that's the way we operate them.

Jack W. Keeley:

That's a different ball game. That is clear-cut.

Roy Williams:

Maybe the solution should be operating landfills on a contract basis.

Paul Plummer, Miami Conservancy District, Dayton, Ohio:

On the last statement, all you have to do is look at the strip mine operators to see what effects you are likely to have and the type of reclamation proceedings you're likely to get. You know, the law says now that they must clean up the site and reclaim the site. Go look at some of these reclaimed sites. I think we as geologists, hydrologists, etc. are going to have to make recommendations to the legal and political people so that some of these problems can be solved by legal means. How we arrive at these recommendations, I don't know.

Truman Bennett, Ranney Water Systems, Columbus, Ohio:

I'm sure that in an individual case the contractual relationship would be very successful, but as a political fact it would become something you couldn't live with after awhile because you won't negotiate in the same way with every contractor. Then everyone who has an axe to grind has a place to grind it, and the sanitary landfill then is going to become a political question instead of the technological question which it should be. Maybe what we are talking about is the possibility of operating sanitary landfills as public utilities.

Michael Apgar:

What we are looking at here, as mentioned in Dr. Zanoni's paper this morning, is that landfills haven't yet been fatal to anybody. So, while we're concerned about ground-water pollution, the alternative is one that results in letting refuse pile up in the streets which is a much worse alternative than letting them go ahead and pollute ground water. I think that laws are coming and pressure is coming that will force operators to clean landfills up, to take care of them in the same way that strip mine laws are now taking effect. There are still some mines that look like they are in bad shape, but there is a terrific improvement in others. That wouldn't have been the case several years ago without the new laws.

Robert Kaufman, Desert Research Institute, Las Vegas, Nevada:

I'm supposed to be taking the place of Dr. Zanoni. The contractual part of engaging in landfill garbage disposal can go three ways—municipal, municipal supervision with private contractor, or straight private contractor. In any case, except perhaps the first, it is a matter of contractual law. To guarantee performance as in any other business operation where there's a risk factor or competence factor, there is simply a matter of posting a performance bond. The most serious problems from solid waste are the future operations. Last time I heard it, Utah was not concentrating on the existing industries and polluters, but rather on controlling future polluters or potential polluters. They are interested in future industry and how it is tooling up with respect to air, land and water degradation as a by-product of its operation. So, if we look at sanitary landfills and the well documented mounting refuse volumes, the object is not so much to attack with an ex post facto law which legally probably wouldn't hold up, as it is to go after the coming problem.

And this is simply a matter of when negotiations come up for contracts for refuse hauling, the contracts should be written with some meat in them. I know in the Las Vegas area the contract from the city and one carrier who has had the contract for over 10 years and wants to negotiate for another 10 years simply calls for hauling the refuse out of the city. Whether he piles it or burns it—the city says that's the county's problem. This is childish. Each is trying to pass it on to the other. So really it is a matter of strong contracts with performance bonds for any dereliction or abrogation of the contract. Now as far as going after existing landfills and polluters, I don't think you can tell them to stop. That's ridiculous. New York City didn't stop for too long; no city has. It's a matter of putting a compliance schedule into any hearing's policy, most commonly with air polluters and big water polluters. They're still polluting, but six months from now they'll be polluting less, and still less a year and a half from now. This is a reasonable way to go after it. If a contractor feels he can no longer provide that kind of service and put in this special equipment, then the contract has to be renegotiated. It is a bilateral contract. The contract conditions are changed if the State or city says you now have to put in this or that for control or diversion works. So what it really comes down to, when you want service in solid waste disposal and a first-class refuse disposal operation, you are going to pay for it. The best way to get into a bad contract is to not have competition when the specs are drawn up and the contracts bid on. The worst condition is to have one bidder, because he names his prices and the city feels they are stuck with it. But there is nothing more secure than a municipal contract and especially with refuse. It is going to be there always and it is increasing.

So my feeling is that we know enough now to operate landfills. It is really a matter of legal and legislative controls and just good, plain contract law to get it to operate. If we are working with details of one site here vs. another site there, I firmly believe that there is enough known now to design a landfill to operate with certain pollution outputs. And I don't think that digging up the old skeletons to stop landfills is really the heart of the problem. The future is the heart of the problem.

Russell Stein:

I'd like to comment on our situation in Ohio because I think we have a real problem in solid waste because it is a pretty populous State. I work primarily in evaluating new landfill sites which I don't think is really that much of a problem now; we have these under control. One is required to obtain a permit from the State before one can operate a landfill. So we have some control here. The problem is this in Ohio—the permit system for landfills was effective July 1, 1970. Prior to that time we had about 600 open dumps and a few landfills. Now what have they done since then? Many of these open dumps have been shut down and there have been about 200 permits issued for new acceptable sanitary landfills, yet there are about 350 open dumps still operating because they can't come up with a site which is suitable for the technical people in the State. They will choose a site, and we say, no this isn't acceptable. So, consequently they continue to use their open dump. We have a time lag here of over a year. I think our pollution problems go back to a lot of these old dumps in which the local people applied for a permit to convert an old dump to a sanitary landfill because it was the only or maybe it was the best site they had in an area.

It still boils down to economics, and you simply can't impel people to pay much more for solid waste disposal than they are now because they just won't accept it. They'll take it out and dump it along the highways like they used to do, and probably still do in a lot of areas. I think this is one of our main problems. It seems like we technical people in the State set our standards pretty high for selecting a suitable waste disposal site, and I found myself kind of giving in a little bit from this respect because there just aren't this many sites available; or if they are available, the people just won't accept the cost of trying to develop the sites.

Richard Pearl, Colorado Geological Survey, Denver:

This comment pertains to Wyoming where a city had the advantage of expert hydrologic advice, but disregarded it and located their dump right over their city water field. The U.S.G.S. office in Cheyenne pointed this out to them and did almost everything but go to court. The city fathers felt it was better to face future water pollution than to face air pollution because the other site, the dump, was up-wind from the city of Cheyenne; and there is some burning at this dump, so they chose to put it over their well field. The question I want to ask Bob Kaufman is how are you really going to get around it when a city ignores expert advice? There is no State control up there.

And then I want to ask Mike Apgar a question. The water level is about 150 feet or deeper up there in this arid to semiarid environment. You didn't show conclusive proof that your leachate was reaching the water table this morning. At least that was my interpretation of it. Is there a chance that this leachate is going to get down there or is it going to be purified enough so that it isn't going to bother the water quality if it does get down there?

Robert Kaufman:

Well, we have a democracy and for all its bad and good points, if an issue comes up, I think the best route is a public hearing where there are expert witnesses, not paid experts, not out-of-town experts, but groups like the League of Women Voters, or various environmental groups. There was a development in Las Vegas recently where over a million dollars was spent on site evaluation, just evaluation, and the return on the investment was reported to be somewhere in the order of 100 million dollars. Now the only objections put before the State were put forth by unpaid, nonprofit interest groups who were in violent opposition to changing water quality standards in the Colorado River, and other variances that this firm wanted against county ordinances regulating the development. The point I make is that an informed public which may consist of just interest groups can bring out a lot of these sticky little issues like putting a dump over a well field.

Now, looking at the other side of the coin it might not be a bad idea. George Hughes has one landfill site in northeastern Illinois on the banks of the DuPage River, I believe it is, and he figures there is something like a maximum of 5 or 10 milligrams per liter increase in chlorides from that landfill site. Now there isn't a person in the world that can taste 10 milligrams per liter of chloride. I'm not making an excuse for it, but you could put this over a giant well field and the landfill is dumping out maybe 20,000 gallons a day and you are pumping 5 million gallons a day out of the well field. It's inconsequential.

Landfilling is a community service. We have buses outside now dumping diesel fumes and we are accepting the service. George Hughes has proved in Illinois that 90 cents out of every dollar is spent on transportation. For every solid waste dollar, transportation eats up most of it. Either go to rail haul and get the economies of mass transfer, or pick a site close in, and the money saved can be used to divert the leachate.

These are the sorts of issues and the questions that have to be generated for each issue, either on the part of the State or with local groups. I think the worst cases develop when things are done in closed meetings and an under the table contract is let for 10 years of service which has no concern for these matters. And I think in the interim, before we have State agencies that are well funded to inspect and regulate and so forth, that we have to depend on the local semipolitical groups and action groups to work with. I don't see any alternative because city and municipal leadership is going to adopt the least cost solution in most cases, because nobody likes increased taxes and you don't get voted back into office with increased taxes.

We have a State law in Nevada now and the only reason it was passed is because the agricultural interests were exempted; they contribute a major part of the solid waste in the northern part of the State. They said if you want support for this bill, exempt agricultural waste. It was a limited victory because the legislature only meets every two years; and if we wanted any solid waste legislation, it had to be without the agricultural people included. Maybe in the next two years we will pick them up.

Michael Apgar:

I think that Bob already answered my part of your question—that you can't really be sure in this type of setting that the landfill is going to have any more than minimal effect on the ground-water quality. In a semiarid environment with an aquifer 150 feet below the surface, you probably won't even notice the effect of the landfill up there, but I'm guessing. I wouldn't want to say that for sure without looking at the site a little more and knowing a little more about it. If they want to go ahead and do it that way, it doesn't sound that bad.

Roy Williams:

Mike, I would like to comment a little further on the problem of saturation. Your paper is a super important paper because it is one of the few that has reported on the water quality in the unsaturated zone. I'm a little concerned that it may not be unsaturated because the 200 foot water level doesn't mean the water levels are 200 feet, and the absence of nitrates suggests anaerobic conditions which may suggest saturation. I would like to hear comments on your evidence for unsaturation.

Michael Apgar:

Generally there aren't any major perched systems between the land surface and the water table, except that we do have evidence that water is standing in one of the refuse cells in the lower topographic position. Sometimes there is water ponded in the upper refuse cell because after a certain amount of decomposition, the floor of these refuse trenches becomes impermeable enough to hold water. Soil moisture contents of samples that we cored beneath these refuse cells only range from 10 to 20 percent, and there is nobody in the area that has a hole in the ground that has water standing in it anywhere between 200 feet and the surface.

Don Langmuir, Pennsylvania State University, University Park:

We have a water table map which was not shown today which indicates the general water levels throughout the whole area and they are around 230 feet or so with very little variance. It is quite a flat water table. So as Mike said, there could be locally some saturation when the soils are appropriate for this, but in general this is not the case.

Jack W. Keeley:

Let me interrupt just a moment and ask a question. Can we necessarily assume that because a zone is unsaturated, it is aerobic?

Don Langmuir:

Whether the zone is aerobic or not is really going to be a function of rates. It is a function of the rate of depletion of the oxygen by organic material versus the rate of its introduction into the system by movement through a soil or in fresh soil moisture. In most cases if there is much BOD, say 10 milligrams per liter or so, and you are talking about a soil, the depletion rate is faster than the rate of introduction and anaerobic conditions will exist because the rates are favoring this. We found in our system, for soils that are heterogeneous, aerobic zones adjacent to anaerobic zones because of the nature of the soil in the system. So it isn't a simple matter.

Roy Williams:

For future studies, I think it would be advisable to put in a few well points just to dispel all doubts that you really are dealing with unsaturated conditions. If somebody comes along two years from now and wants to use your data in a decision, there will be absolutely no doubt.

Michael Apgar:

We have a similar study involving a program of spray irrigation of treating secondary waste effluent from the University Sewage Treatment Plant on a game land area. We are dealing with the same type of soil, same underlying bedrock, and same water table conditions at depths between 200 and 400 feet below the surface. Pan lysimeters were installed in the soil, and they just couldn't get samples in them. That is why we are using suction lysimeters. Now there are pan lysimeters in use in the spray irrigation study, but they only collect moisture after the soil is essentially saturated by heavy spraying directly over where the lysimeters are located. I am not saying that there aren't positions in the soil, especially after periods of heavy recharge, that aren't saturated. There may be small perched systems on clay lenses and unweathered bedrock ledges and things of this nature, but in general you don't get much water. If you put a hole in the ground, you're not going to get much out of it. You can be fortunate enough to end any hole or piezometer on an impervious ledge and have water standing down there on a regular basis. But it just depends on where you locate the end of this thing. And to get samples we went to suction lysimeters.

Jeffrey Sutherland, Williams and Works Engineers, Grand Rapids, Michigan:

I'd like to ask Don Langmuir and Mike Apgar a question related to their paper this morning. I'm unsure of how you are able to determine that leachate from the upper refuse cell contaminated the ground underneath the lower one. It seemed to have had a rather shallow topographic slope between the two, and no perched water. Therefore it doesn't seem to me that much of a route for horizontal transport was present. Maybe I'm missing something here.

Michael Apgar:

I'm sorry if I gave you that impression. The figure I used in the talk was a plot of depth versus conductance beneath the cells. But the instrumented cells in question are on opposite sides of this dry stream bed and so we're not saying that leachate from one actually goes down and reaches the sampling points beneath the other. But rather there are a series of cells all along both slopes and the cells located above the valley bottom cell on this side of the stream bed may in fact move down and make any soil moisture contamination problem beneath the lower cell look worse than it might be if it received a contribution only from that cell.

Jeffrey Sutherland:

So there is enough of a stratification in these soils or sediments to get some lateral movement from one cell to the next?

Michael Apgar:

Well, I wouldn't say it is a very regular stratification. The soil bottoms slope downhill and the topography is going that way and there is an outcrop located about 700 feet away in which the dip of bedrock is in the same direction as the slope here. But of course the soil itself, even though it is a residual soil with some lenses, layers, and regularities, is fraught with all kinds of collapse features and mix-ups that developed as the rock weathered. So it's not a simple situation where you can put things in at the top and let them float downhill.

Jeffrey Sutherland:

I have another question. I'm new in the landfill site evaluation business myself. In Michigan I'm acquainted with the regulations established by the Michigan Geological Survey which is one of the two State regulating agencies. We have a lot of apparently homogeneous dry sand terrain without much in the way of low permeability layers like clay to afford some kind of a natural collecting substrate for gathering leachate into some kind of a treatment system. I wonder if anyone has any experience with bentonite or any kind of liner that can be harrowed or disked into sand to minimize or perhaps eliminate any significant liquid leachate percolation?

Paul Goydan, Koppers Co., Inc., Pittsburgh, Pennsylvania:

Of course today many of your State agencies require bentonite as the lining to use in lagoons and other types of installations where you expect contamination of ground water. Bentonite may be purchased from a number of agencies. Wyoming bentonite, which is generally regarded as one of the best bentonites as far as being impervious, is pretty much a sodium montmorillonite clay. You often get involved in Arkansas bentonite and some of these other States that claim to have bentonite. You are dealing then with a mixture of clays; and although there may be a certain degree of montmorillonite this is often calcium montmorillonite which is not as impermeable. Some research has been going on as far as taking a clay such as a calcium-rich montmorillonite with a mixture of kaolinite and chlorite or whatever else you may have and impregnate this with salt water supplying the sodium. This can be used as an impermeable type bed; and, of course, through time, your lattice structures in the clays will expand and improve your barrier. Did that answer your question or were you talking about absorption rather than sealing?

Jeffrey Sutherland:

I was asking whether or not the properties of sodium bentonite or sodium montmorillonite actually do provide a maximum seal to minimize or absolutely prevent the formation of leachates.

Paul Goydan:

I've found a statement that 10^{-7} to 10^{-9} centimeters per second permeability is expected. This is the permeability range of a good Wyoming bentonite. This is considered "virtually" impermeable; and without going to some cementing material or manufactured material this is pretty good; and with an expanding lattice, with water, you don't have too much to worry about.

Don Langmuir:

Might you than have to worry about the nature of the leachate itself altering the characteristics of the montmorillonite if it is a calcium or magnesium leachate? Ion exchange can alter the permeability of your liner if the leachate-liner combination is not compatible.

Joe Miller, New Jersey Geol. Survey, Princeton:

We have a similar problem. I was talking with Mike about it. The County of Camden is going to make a county sanitary landfill on 450 acres in an area where it is 27 feet to ground water. We are trying to figure out what the heck we can put down to keep the stuff from going down. So far I don't know whether your bentonites are going to stand up, because we don't know what they are going to put in this landfill. Any ideas on something like this? What about putting an impervious layer with perforated pipes and then transporting the leachate back into a municipal system. Is this acceptable?

Grover Emrich, A. W. Martin Associates, Inc., King of Prussia, Pennsylvania:

This raises a very interesting question because we are now completing the engineering and construction of a limestone quarry that will be turned into a sanitary landfill. The quarry had about 30 feet of water in the bottom of it. Submersible pumps have been installed to lower the water table and maintain it below the bottom of the quarry. The quarry is being filled with rock and earth to bring it up about 15 feet above the water level and then an impermeable liner will be put in. We are disking soil cement in the upper foot of the soil and then we will put on a specially prepared tar pitch material that will be sprayed across the bottom of the quarry. It will be sloped to a central sump from which the leachate will be pumped to the surface; it will be treated and then discharged into a nearby sanitary sewer. This quarry will be reported at the AAAS meeting in Philadelphia this winter. If any of you are interested in details I'll be here for the rest of this evening and tomorrow morning.

The quarry should be in operation toward the end of September. Unfortunately Murphy's Law has come into play and we are now 9 months behind in completion of the quarry. Murphy's Law says everything that can go wrong will go wrong, which included an operating engineer's strike for three months. Power lines were not there and it took three months to get them in and things like that. We are also doing the same thing for another quarry which is a cement quarry north of Allentown, Pennsylvania. Cement rock up there is fantastically tight. All the people use cisterns, not because their water is polluted but because they don't have any water in their wells. We will go through the same sequence of dewatering the quarry which has about 5 feet of water in it, building the quarry floor up, putting in the liner, collecting the leachate, treating it and then discharging it to a sanitary sewer. Another landfill is in operation in southeastern Pennsylvania with a liner in it. This has been in operation since last October. They also will be collecting leachate and treating it. In that case they will discharge directly to the Delaware River Estuary. The technology I think has reached the point where we can hydraulically isolate landfill leachate from the ground water, treat the leachate and handle it just like another industrial waste.

There is a possibility of putting a cover on top of the landfill. This has been tried many times. I've worked with Pennsylvania regulatory agency setting up the regulations and doing all the hydrogeologic investigations. In fact, this Penn State study was something that the Pennsylvania Dept. of Health initiated by going to Penn State. There was another one we initiated at Drexel University. My staff and I have looked at 100 or 150 landfills designed specifically in an attempt to put clay covers over them to keep the water out and no leachate from forming. They have been notoriously unsuccessful—I'd say 100%. There are several reasons for this—the decomposition of organics and other materials in the refuse will produce a liquid. Of course if you have no moisture in it, you might delay this. In most cases they use a clay cover which is improperly installed. It is wet, it swells, water runs off, then it dries off and it cracks. I've seen some cracks that are 2 or 3 inches wide and many feet long so that the next time it rains all the water runs down the cracks. There is very little that runs off. Another problem you have is that even with an impermeable clay layer on top you still have your gas generation. Some of this gas may move laterally; unfortunately, it will build up pressure and will crack your liner. I cannot recommend the idea of making it impossible for leachate to form. I've yet to see it work; and, unfortunately, it has been sold. Maybe somebody else has seen it work. I'd be interested in anybody that could fill me in on this.

Ted Hudson, Radian Corporation, Austin, Texas:

Has anyone done any work on the equilibria that are set up between the absorption of the various organic compounds that are going to be produced in the leachate and what effect this has on the permeability of a clay liner? What are the equilibria that are set up and what does this do to the permeability of the clay liners that people are talking about using? Which is preferentially absorbed, the organic, the sodium, or the inorganics that are in the landfill?

Don Langmuir:

To my knowledge, there has been no detailed study of sorption of the organics. The charged species you would primarily be concerned with are going to be anions, so it's anion exchange. Most clays are cation exchangers so that they're not going to play an important role. It is more likely to be a factor of the accumulation of these materials on trench bottoms. Mike can tell you a little about this. There is a physical clogging effect that these organics will have on clay liners, where leachate is trying to flow down through the bottom of the trench. You'll get slimes and gels which prevent the flow of the leachate, which will decrease the permeability. Since in most cases cation exchange is predominant, the inorganic cations will be the favored species in exchange. The sodium, calcium type thing will affect the permeability, of course.

Ted Hudson:

Mike, can you refresh my memory on the pH of some of these leachates?

Michael Apgar:

The pH in leachate ranged from about 5 to 6.5 normally. However, in one case where we dissolved a cement floor and maybe due to some other causes, it got as high as 8.0 or 8.5.

Ted Hudson:

I know there is some work on some chromium oxide absorption on sodium montmorillonite clays that MacAtee and Shaw did several years ago and these things are quite strongly absorbed on clays. Also Hawthorne did some work in which he looked at some positive nitrogen containing organic compounds. They were involved in looking at these montmorillonites as cracking catalysts for various operations. Therefore, they are quite strongly absorbed by these sodium montmorillonite clays. They did not look at the equilibria that were established. They were not concerned with it and I was just wondering if anyone here was.

The other question I have is concerned with your Eh values. I would like for you or Dr. Langmuir to elaborate a little more fully on the oxidation reduction potentials and what value you placed in these redox potentials in your interpretation of your data.

Michael Apgar:

I don't think anybody that has been studying leachates from landfills has made the jump to trying to figure out any kind of equilibria absorption relationships between organics and soils because most people don't even bother with identifying the organics. I can remember reading one study where this was done and we're thinking of getting into this at Penn State, but ground-water geologists with a chemistry background are generally inorganic chemically oriented. It is kind of a sticky business, and not much fun either, to collect this highly organic contaminated slop and take it in the lab and play with it. To fool with the organics is something that hasn't appealed to many people yet. I don't even know if they have considered doing it.

I can remember a study in West Virginia where column experiments were carried out. Leachates were put into concrete cylinders and water was leached through this refuse and collected from the bottom at a spigot or drain and then the organics were identified or separated chromatographically and identified as being mostly acetic or butyric acids. As for carrying this further, I don't know.

I'd start answering the second half of your question but I see Dr. Langmuir is getting very excited about doing this so I'll let him take it.

Don Langmuir:

I was going to comment a little on what you were just talking about, Mike. This organic stuff in leachates is so complicated that you can find anything you like in there. You'll find what you look for. There are not just organic acids. There are carbohydrates, fats, proteins, you name it. You could spend a lifetime trying to discover which things were there. And that's why it's so difficult to figure out what anything is doing in terms of its effect on, for example, trace metal transport. This kind of thing we're going to try and get into in the next few years.

I'd like to talk about the Eh thing for a minute—as I said this morning in an answer, we worried about this quite a bit. If I can get back to the beginning on Eh, it might be useful. An Eh measurement is going to be a measurement of a zero current flow at a particular potential. There is no current flow and you find that potential at which this current will not flow using a platinum electrode and a reference electrode. For this to occur there are two voltages involved; there's an oxidation and a reduction voltage potential. You need reactions which are reversible to get a meaningful Eh measurement and this can be an awful problem if you've got a whole series of different species, some of which can be reduced but can't be oxidized, and conversely.

Now this is what a leachate is in many cases. You've got nitrogen species which can be oxidized, you've got sulphur species which may be or may not, and you've got a variety of reactions which are not reversible. But there is a way out of this. In many cases a leachate is very, very rich in iron, and the total iron values Mike was talking about are chiefly ferrous iron. It has been found that the reaction between ferrous iron and ferric hydroxide is ubiquitous in the leachate, because of the iron in the soil. This reaction is reversible and it goes fast. There is a measurable potential from ferrous iron to ferric hydroxide and back. And this is what seems to be controlling our measurements. It makes good thermodynamic sense in spite of the mess a leachate is to make this assumption. We can compute things about this reaction from the measurements we make of pH, Eh, of our assumed solubilities for the oxides, and it works. We didn't show the plots today. We have plots of measurements in the leachate and they parallel right on boundaries, ferric hydroxide, ferrous iron, if you know what those look like on an Eh, pH diagram. They make pretty good sense. There's one up there Mike's waving if anybody wants to look at it later on. So we don't want to take these numbers and say they are thermodynamics in the pure sense, but they work reasonably well. For example, they seem to tell us that we will not have nitrate when we're way out of the nitrate field in that diagram—for example when we're way down in the ammonia field. They give us a pretty good semiquantitative view of what is in there and what to expect.

Paul Goydan:

Did you look at the reduced and oxidized species of nitrogen? Were they able to give you similar type indications of the Eh, and also of the oxidized and reduced sulphur species?

Don Langmuir:

We didn't see oxidized species of nitrogen except at the very beginning of the study when anaerobic conditions were setting in, and at that time I don't think we had Eh measurements. So most of the study conditions were anaerobic enough so that we had no nitrate or nitrite.

We don't know exactly what the organics are but there is a tremendous literature now of organic interactions, as you know, with clays; and at Penn State, George Brindley has done a great deal of work of this kind. Of course, the gap between knowing what the organic is in a pure system and what it really is in leachate is a long way.

Ted Hudson:

My only thought here, as Dr. Langmuir has pointed out, is he doesn't really have a pure thermodynamic ferrous, ferric system in which he makes his Eh measurement or his redox potential measurements, which is fine. It doesn't really matter because he gets the information he is interested in. I would not like to trudge out there and collect these samples either. Nor would I like to use them in the laboratory. But if one made model compounds and then made these studies you would have some basic understanding of the competitive nature of the reactions between the cationic organic materials and the cationic inorganic materials. This is the point I was trying to make.

Don Langmuir:

In the future, what we plan to do is look at some of the organics as they move down through the soil—look at the BOD and break it down in terms of certain types of organic chemical species—and see how they vary in amount and type with depth. This should give us some kind of an idea of what is going on. We'll relate this to trace metals and to absorption if we can.

Jack W. Keeley:

I'm going to get in trouble here. We've talked about how we like to go out and measure pH and chloride and sulphide, etc. I asked this question this morning and I think it's one that we very often ignore, probably because we are afraid of it or we don't know how to handle it. I can at least imagine situations of zero BOD, zero chlorides, zero sulphates, zero this, that and the other, and we have some highly carcinogistic materials, or their degradation products, that totally escape us. I know DDT degrades anaerobically. We don't know what the degradation products are. They may be more soluble. They may be more toxic. The world is full now of antibiotics and estrogens, of birth control pills, and diethylstilbesterol which we feed to animals. I think we tend to completely overlook this field because it's difficult. Do we have the latitude to be that pious to simplicity?

Ted Hudson:

Also overlooked are things that are precursors to carcinogens. There are many compounds that react with other things that then create a carcinogistic compound. So I call these, or lump these, into what is called a precursor to a carcinogen. An example of this is nitrite. If nitrate is present, you have the possibility of nitrite. Nitrite can react with various and sundry compounds to form nitrosamines which are known as carcinogenic compounds. I just throw this out to say that the subject matter is even more complicated in that you have also these precursors to carcinogens.

Jack W. Keeley:

Then we throw all of the degradation products of all of these together and we've got a mess. Does anyone wish to comment on this before we move to other questions?

Paul Plummer:

We are probably sampling what we can measure. A lot of these things, even sampling for trace metals, gets extremely complicated. And once you get outside of the laboratory into a practical field situation, it becomes almost impossible to get what you consider to be a valid measurement of some of these substances. There is room for a lot of work on sampling techniques and methods for measuring these many trace elements which we are introducing into the system.

Jack W. Keeley:

I can't accept that because something is difficult we in the ground-water industry can ignore it. I have been in the field a good deal myself. There are techniques available and there are possibilities to develop new techniques. What I am suggesting is that we in the industry should be forward thinking enough to start getting into these. I realize you can't go out in the field with a bucket and a rope and concentrate samples to where we can shoot them into a gas chromatograph and look at these things. I'm suggesting here that we start looking at them. Let's lead the surface boys a little bit.

Don Langmuir:

There are a couple of ways we can go at this whole thing. From major species we have various defenses; for example, if we have charged species to see if we've got everything in there, we measure the total anions and the total cations. They've got to equal each other. If something is in there we don't know about, we'll find out that way. So insofar as we have major species over 2, 3 or 4 percent, perhaps, we can spot them often this way. This is the inorganic charged species. We've got total dissolved solids and we've got conductance. We've got a variety of total measurements as a means of getting at the summations of other species in the system. Beyond that point, when it comes to trace species, we've got to go to other techniques such as spectrophotometric scanning or neutron activation. There are various new devices and new ways of getting at a variety of things that may be in there. We ought to develop more of these techniques; for example, scanning for the trace species. That's the big problem, as you say. What is there in the trace amount which can hurt us? That's where we need the most advancement, the most research.

Bob Kaufman:

I don't want to drag down the scientific level of our preparation for Dr. Greenfield. I'm not arguing with any research goals. The point I'm making though is we have to service a community problem. NWWA has come up with well drilling specs, completion specs and so forth; maybe they are not the best but they are the best the NWWA could come up with at this time. The point is that there has been enough work done on the hydrogeology and chemistry of landfills that we can provide a lot of service and advisement to practically any major problem in the country. And I dare say if we had an interchange like this tonight in front of a community of concerned citizens at a local hearing, these people would be very astray as to which course of action to take.

I'm not arguing with anything you've said, Don, or the gentleman from Texas; but I think as others have pointed out today, Al Zanoni for one, the garbage trucks are coming down the street. Now we can bury it or we can burn it. Those are the only two alternatives we have, and there's enough knowledge to provide a reasonable factor of safety for burial, the sanitary landfill. I can't overemphasize that enough because to go and say we need more study, we've got to find this out, we've got to find that out, is not doing a service now. It may be in 10 or 15 years but it's not doing it now. I don't see why we should go into multimillion dollar landfilling operations over a 20 or 30 year time frame with a $500 site investigation. The techniques are available to design landfills to meet certain performance criteria and when all the other information comes along later as to exact knowledge, fine. Maybe I'm just a marginal scientist, but we have a today problem and more study, the data of which and conclusions of which are available in five years, won't meet today's problems.

Warren Hofstra:

One thing that has impressed me a lot is that people are looking at these things from a very practical, today standpoint. But I question whether the water system in the humid crowded portions of the country will stand the total impact of solid waste disposal, septic tanks, industrial wastes, and all of the other things that are going into the water system. I think that as a practical matter we will have to develop the best sanitary landfills that we can for the time being. But I do feel that we are allowing a five percent change in the water quality with this landfill. I feel that we are, in the name of practicality and economy, perhaps overlooking a more thorough and a more complete control of solid waste and all waste. Perhaps we are being a little short sighted considering a tremendous increase in population, and I think we may have to reclaim these materials.

Bob Kaufman:

I agree, the average site investigation today is absolutely minimal. I don't think we are in disagreement. What I am trying to say is we are not using the tools that are available. This is the problem. If a community goes for any kind of a major capital investment such as landfilling, it's a 10 or 20-year operation in practically every situation. A town of 250,000 will spend a million dollars a year in landfilling. Now, a million dollars a year is a capital investment that should be handled carefully with long-term goals. For instance, if we put in a landfill in a human zone, we can control infiltration to a certain degree. There can be tile systems put in as the refuse goes. It can be incremented over the years as the landfill expands. After the infiltration is reduced, either through control of runoff or proper vegetative cover or using it with a very tight asphalt cover for parking lots, we use the tile systems to collect leachate; and if things still get out of hand, diversion wells can be put in. We have talked about dewatering before refuse is put in. We can lower a water table after it's affected. I don't see anything wrong with this. An engineer, for all his skills, plays every bet he can. And when he is in doubt, he puts in a factor of safety. Geologists think that they're putting their tail between their legs if they start talking factors of safety. And yet geologists should be the last ones to be exact. Who can say how a bentonite line is going to behave after 10 years of leachate contact? We can't wait 10 years to find out.

Dick Rhindress, Pennsylvania Dept. of Environmental Resources, Harrisburg:

I am directly involved with our sanitary landfill program. I just walked in so I'm not sure what has been said. But picking up the shreds of the conversation here, we've tried to tackle this by the horns and run with it. We agree that there is no single system. You can come to us with practically any plan under the sun to run a landfill. Yes, we have guidelines which say you should run them in these basic manners. But when it comes to engineering and geology and hydrology, if you've got some new plan, we'll listen. We're fully open to anything, whether it's underdrains, lining a quarry with whatever you want to line it with, putting down an asphalt layer on flood plain gravels, whatever you have to do to collect leachate, or if you have a good site where there is a reasonable zone of aeration like Mike's site up at Penn State. We still feel you can probably get away with the natural renovation system. The sites are limited but this is a possibility. We're also open to all the new research we can get. We've been in on the support of the Penn State study, and we've had input into the Drexel study and gotten output. We're in close contact with the Illinois people and everyone else that's doing any of this type of work. We take every little fragment we can get, and we're going to be a clearing house to help you people around the State come up with some good sites.

In the idea of site investigations, we have what we call modular forms. They are forms to be filled out in great detail on geology, ground water, soils, engineering plans and so forth. The geology section of those forms has been written so that only a geologist can understand it. There's about 17 pages of geologic data that we require before we'll even look at your site. So we are at least forcing the landfills in Pennsylvania, the new ones and the old ones that have to be upgraded, to come in with one raft of geologic data before we'll even talk to them.

Jim Urban, Agricultural Research Service, University Park, Pennsylvania:

It seemed to me throughout much of this discussion this common thread of getting rid of waste by dilution seems to occur. I wonder if we might consider a pollution potential somewhat analogous to a dam. If a dam is close to a city, it requires a higher degree of site investigation than one in the middle of a strip mine area 50 miles away from the nearest population. What do you do when you have an area where the ground-water quality becomes impaired to the point where you reach, say nitrate nitrogen at 15 ppm? Where do you stop your inputs? Do you stop putting in landfills at that point? Just where do you draw the line on inputs? Can you allow these inputs to occur?

Michael Apgar:

I don't think you really know what the impact on ground-water quality is going to be until you go ahead and do it. It's just like aquifer modeling programs right now, or in the development of a model for any kind of a hydrogeologic system you want to play with. You really don't know how the model is doing until you go ahead and do it and check the results. Once you see that you're contaminating water from a landfill in an area, well, you're contaminating the water. I don't know if that answers your question or not, but in a lot of cases you really can't be sure how much contamination you're going to get.

I want to make a comment also on some of the implications of the Penn State study that we've been doing. Sure, beneath at least one of the cells that we're instrumenting we see that the leachate is not being very effectively renovated as it percolates down through the soil. It is of horrible quality to begin with and it seems to be going down to about 50 feet now. But in other settings the leachate is being effectively aerated and diluted so that really it is not a problem by 20 or 30 feet. And you have different things going on within the same site. This depends on how much water you get in the cell and what kind of refuse materials you've got there anyway because it is heterogeneous all over the place; and, as far as an impact of this landfill on the water quality immediately beneath the site, there's a deterioration in ground-water quality that we feel confident is due to the landfill. Now, of course, we only have the one monitor well which is a problem.

In any case, whether or not landfills are going to affect anybody beyond the landfill at the next water supply or something like that, I'm pretty sure that it's not. The next water supply might be for watering a golf course half a mile away and is probably not even in the same flow direction. By the time you get the water that far away it will probably be mixed up and diluted with other things so that it's not going to be a big deal. They're not going to kill anybody further away.

I'd also like to take this opportunity to change the subject. Here we are out in Colorado and nobody seems to be very worried about leachates from mine tailings, when it has already been shown that such leachates have killed a horse and maybe a man, even though he doesn't want to know what's killing him. Whereas leachates from landfills are a more widespread problem, we haven't really demonstrated that they are of a toxic nature. We're just talking about increasing the solids' content of water or making the water kind of smelly, and you can get around this. If leachates foul up your water supply to the point where people won't drink it anymore, they can always treat it and this will cost them money on that end rather than the other end. And that's not a good thing. I think we ought to give Leland Mink a chance to talk a little more about his studies with the metals from the mine dumps.

John Rold, Colorado Geological Survey, Denver:

There's been a lot more concern about the problems of leachates from mine tailings than is apparent on the surface. Yet I think we have less problems from mine tailings here in Colorado than we have from sanitary landfills. Zanoni's paper today gave the impression that sanitary landfills were not really much of a problem in general. The same comment has been made again tonight. When I was down at the office this evening doing some work, I saw a news release from U.S.G.S. which was quite interesting in light of our discussion today. It's from Earth Science dated August 22. Many of you will probably get this. On the third page it says "Although there are several hundred documented cases of pollution caused by leachates from solid waste disposal sites, few contain data on the magnitude of the pollution and its effect on the hydrologic cycle." We have several hundred solid waste disposal sites here in Colorado in the alluvial gravel of the South Platte River. We can't say it's in the past because there is a new one starting in Adams County right now. It's the same thing, a water-filled gravel pit that's going to be used as a sanitary landfill. How much damage has this done? I don't know except that below Denver and downstream from Denver for quite a few miles you can't drink the ground water. Now what has caused it? I know of two monitoring attempts on sanitary landfills. One of them was an old landfill and all they could tell was that the water above the landfill was just as polluted as it was below the landfill. So you'd have to trace it farther upstream to find out what the first landfill really did to it. And another one, of course, just went in and proved what we thought; leachate was coming out of the landfill and going into the gravel, but nobody seemed to want to do anything about it because we couldn't prove that it killed anybody. But nobody really dies of drinking polluted water; they just quit drinking it, whether it's surface water or subsurface water. So I don't think that it is a very good argument that either Dr. Zanoni or you used. Water is our lifeblood here in Colorado. And we look very longingly at the East where you get dilution. There isn't anything we do with our water here that doesn't hurt it. We just can't do anything with water but what the water is worse when we get through with it than it is when we start. Water from the South Platte doesn't start to clean up again until it gets to Grand Island, Nebraska, and that's too far to bring it back up to Colorado to use it. So we have no dilution factor at all. Going out the west slope to California is even worse. They are beginning to complain even more than Nebraskans about the type of water we're giving them.

Don Langmuir:

Leland, can you give me some details on the techniques that were used in sampling for the trace metals in your study? We've had some difficulty, and we're trying to learn techniques ourselves at Penn State on trace metal sampling and analysis, and I'd be curious if you could elaborate on how you did this.

Leland Mink, University of Idaho, Moscow:

We ran into some problems in sampling, especially the mine waters. The natural waters within the environment didn't pose too much of a problem. As one probably noticed, I didn't mention anything about acidification of the sample upon collection. We collected in a polyethylene bottle and analyzed for a few parameters in the field and then transported them to a lab. Within the laboratory we just allowed the sample to settle, took the supernatant from the top and analyzed on the AA. The problems we ran into on acidification were numerous. First off, we experimented on acidification and found that even though the acidification will minimize the absorption on the container walls, we also were stripping ions off of the suspended solids contained in the sample. And upon filtration we removed a lot of the material within this. Also we found acidification of some of the mine waters caused a precipitate to form which completely eliminated some of the parameters we were looking for. So we found that acidification posed more problems than nonacidification; and by allowing it to settle, we assumed that we were approximating conditions we would find in a natural environment. When these sediments would settle out they would not be available to the aquatic life.

Don Langmuir:

The settling was before acidification?

Leland Mink:

Right—the acidification was experimental. We never did acidify the sample.

Don Langmuir:

You have another problem of absorption with pH changes in plastic bottles because of gas transfer through the bottle walls. A pH change will affect the absorption and can change the trace metal content in the supernatant before you even acidify it. This is a thorny business. People have argued against using plastic bottles because they are so much worse than glass bottles in this regard.

Paul Plummer:

I have a question on standards. We've talked a lot about sampling and various levels which have been set by the U. S. Public Health Service, Drinking Water Standards and others. Are these standards based on total water, or are they all on filtered water? This is a problem we ran into. We are sampling from wells. Do we sample it the way it comes out of the well, or do we filter it through an 0.45 micron filter which, again, is very arbitrary. And how then, if it is filtered, does this relate to what the standards may be? Does anyone have any comments on this?

Don Langmuir:

I think the U.S.G.S. normally refers to the 0.45 micron filter when filtration is considered, and it is normally on a whole sample at that point. You take it through that filter, then you are considering what is in the sample. But that's an awfully important point to think about too. For example, are you concerned about what is transported in suspended sediment in stream load? Because it is a genuine pollutant if it is toxic and on the sediment. It should be considered. Although it may come out of the water supply where you have coagulation and filtration before it goes into the water distribution system, it still is transported and it still is worth considering. What you really have to do is say that the trace metal or toxic material is smaller than 0.45 micron or bigger than 0.45 micron. If you don't do this you're in trouble.

Bob Kaufman:

I'd like to know how many people are drinking 0.45 micron filtered water out of their wells?

Roy Williams:

I'd like to comment on that problem. The EPA currently is suggesting that Idaho, for instance, write standards in terms of what they call total metals which means acidifying the sample, which strips things off and busts up sulfides and gives phenomenal concentrations of zinc, let's say, in water. Very few mines can operate with standards that are being proposed when analyses are done in this fashion. The problem of transporting is not so cut and dried. The ions that are attached to the sediments are undoubtedly transported, but we've got analyses of both the sediments and the water, and there is very little relationship. For instance, lead which is high in the sediments, is zilch in the water. So when you're setting water quality standards it makes very little sense to say let's take the total. Let's go pick up a sample during flood stage when things are murky. You will get a wild reading which is not indicative of what is really in the water.

The other thing that bothers me a little bit is that the procedures being used now are quite variable throughout the country. They need to be standardized in terms of monitoring procedures. We need some nationwide conferences among the monitoring agencies because you get things you can't compare from one part of the country to another as a result of the different procedures that are being used.

Jack W. Keeley:

I think Bob Kaufman made a very profound introduction and I'm surprised that someone didn't follow it up. Are we not really talking about what use is to be made of this water? We take it as we get it. If we're talking about a streamflow that is variable in terms of its silt load which in turn gives variance to the amount of material that is sorbed, and this is what we're drinking, aren't we really getting back to perhaps a statistical base of setting quality standards?

Roy Williams:

Well, most people are no longer (in the Northwest anyway) talking about drinking water standards. Those are way too high for aquatic life, particularly the kind of aquatic life that the pressure groups in the Northwest are interested in preserving. And even if you do consider a statistical base you're still stuck with some technique that gave you a number with which you have to live.

I might make one more comment on this problem. Personally, I feel that the way to go is to let the solids settle out. One thing we didn't do, which we should have done, was let them settle out for a definite, constant period of time and then analyze the supernatant. You've got the contact between the solid and the water to give you a constant equilibrium which you don't have any other way.

Don Langmuir:

Can I comment on the chemistry of that? If you have a plastic bottle with a sample in it and you let it sit on the shelf for a week, it will breathe. Most ground waters are higher in carbon dioxide than surface waters by a factor of 10:100 or more. It is going to go out through the bottle walls, and the pH change can commonly be half a unit or more. If you're talking about absorption on the sediment at the bottom of the bottle equilibrating with the liquid above it, it's going to be messed up by this pH change because the hydrogen ion is competing with the metals. So this is kind of a risky way to go. If you can get it to settle in a day and refrigerate it while it is settling, that may work. Or if you use glass bottles and fill them to the top that will work.

Paul Plummer:

The criteria which I used was if this is the way the people drink it, this is the way we will analyze it. In other words, if the people are drinking water from the well and this has not been filtered through an 0.45 micron filter, this is the way I want to analyze. Now the problem I have run into is, does the data that I am getting correspond with the limits which have been set? I feel they probably don't. I suspect that many of these standards were set at some detectable limit, whatever year they were established. We could detect cadmium to 0.01 mg/l so that's the standard. Since that time we have added a zero to the thing and now we can detect cadmium to 10 mcg/l but I don't think this is necessarily the case in a lot of analysis. Still, it is the total consumption of say lead or zinc that is important. If the material leaves the sediment, it becomes available to the biota and their processes. It is well documented that fish and other organisms concentrate metals; then maybe we really want to know what the total is, including the sediments as well as the filtered water.

Roy Williams:

I think the significance of the precipitation business that Leland mentioned can't be overlooked. Not many people have messed around with mining wastes, and I can take you to an effluent which, if acidified, you could watch the solids precipitate out of solution into the bottom of the bottle. I can only take you to one place where you can watch it. I can take you to other places where you will see changes take place. Somebody needs to look into this in terms of a research project.

Jack W. Keeley:

We seem to be burning out after two hours. Are there any questions?

Joe Miller:

To get back to our so-called sanitary landfills, I haven't heard any mention at all of what these operators bring into the landfills between midnight and reveille in 5,000 gallon tank trucks. This is rather a common practice. Any comments?

Michael Apgar:

I wouldn't say that most municipal landfills are guilty of having exotic industrial wastes dumped into them while nobody is watching. It depends upon what type of industries you have in the area. Who knows what they're doing with their wastes? This can be a problem because some of the wastes that come out of industrial sites are extremely toxic and tricky to handle.

Joe Miller:

It's not only the industrial, Mike. I'm thinking of a pharmaceutical waste which I know was put into the outcrop of a formation, as I said, during the designated hours between midnight and reveille. There are no monitoring wells.

Dick Rhindress:

I think I can comment at least on a partial solution to this. We have recently surveyed by mail, and we're following up with on-site inspections by our industrial waste people, finding out what products are made, what by-products are likely, and what the wastes are going to be. And we're asking what they are doing with this specific waste. If we know it is the kind of plant that always generates phenol, for example, we go in and ask specifically what they are doing with the phenol. Half the time they tell us they're taking it to New Jersey or something like this. At least this is a partial solution. I realize we're not going to get the gospel truth out of all these companies, but it is a start at preventing the midnight to dawn dumper. They still exist though, I realize.

Bob Kaufman:

Jack has asked me to take over for a few minutes. Any more questions on the landfills? I have a comment for John Rold. How many publications has the U.S.G.S. had on sanitary landfills? I know of one. You made the comment that the U.S.G.S. had documented 700 cases of pollution from sanitary landfills.

John Rold:

They said they were documented. They didn't say they had done it.

Bill Seevers, Geraghty and Miller Inc., Port Washington, New York:

The only point I raise is the fact that sanitary landfills are associated with our populated areas. This is where we live. Mining problems are in the relatively unpopulated parts of the country. There are regions in the Northeast where we are simply running out of space; and in a sense, this is part of the problem with sanitary landfills. We've got the physical problem of the landfill, but we also have the space problem. So this is why I view it as a rather serious situation.

Dick Rhindress:

Aren't we really saying that we've got to dedicate some land to landfilling, and are we saying let's choose the best techniques we have and use them in landfill design. Or, are we saying that we have a fairly good handle on how to clean up the leachate from landfills by collection and treatment systems or natural renovation at very good sites. We do have a pretty good handle on it, and it is something we can control. In the case of mining, we still don't really have our technologies down anywhere near where we do on landfills.

Jack W. Keeley:

Are there any pertinent questions? The hour is getting late. I'd like to make an attempt at summarizing very briefly. First of all, with respect to landfills, it appears that we do have sufficient technology available to install sanitary landfills. We should use this technology as best we can because the garbage truck is coming. We can make an analogy here to all types of engineering designs where we enter into them knowing that there is a possibility of failure. We can, with the knowledge available, reduce this probability. Further, we realize that there are things yet unknown, and we will continue to improve both our techniques to measure and our abilities to control. We have pointed out that there are several techniques available to handle leachates from landfills. One may or may not be appropriate at any one location and we are mindful of this. We are also mindful that in dealing with a ground-water resource we must be a little more careful because a ground-water resource once polluted remains polluted for a protracted period of time in comparison to a surface-water resource.

With respect to mine pollution, it seems that we dealt mostly with our ability and inability to sample, measure the contents of that sample, and understand what that measurement describes.

Now then, are there any additions, omissions, or corrections? Then let's adjourn.

Methods of Geologic Evaluation of Pollution Potential at Mountain Homesites[a]

by James P. Waltz[b]

ABSTRACT

Development of mountain homesites is accelerating in the Rocky Mountains of central Colorado. These homesites often require individual water wells and sewage disposal systems. Unfortunately, the widely used septic tank-leach field system generally is not suited for use in the mountainous terrain where soils are thin or missing. Although current federal regulations call for six feet or more of soil at the leach field site, many of the individual sewage disposal systems now in operation in the Rocky Mountain Region of Colorado fail to meet this requirement. Sewage effluent at these sites may directly enter bedrock fractures and travel large distances without being purified. As a consequence, contamination of streams, lakes, and ground water from these malfunctioning leach fields has become a problem of increasing magnitude.

Investigations of geologic, topographic, and hydrologic conditions at over 100 homesites in the Rocky Mountains of north-central Colorado have resulted in the development of objective criteria for evaluating pollution potential at mountain homesites. In addition, the results of these investigations indicate that contamination of water wells may be decreased significantly where geologic conditions are considered in the selection of sites for leach fields and wells. Although the results of these studies should be considered preliminary, they do tend to confirm that the orientation of jointing surfaces in the bedrock significantly affects the travel path of contaminants.

The press of our growing population and the increasing affluence of our society have resulted in more and more people buying homesites in the scenic and relatively isolated mountainous area of central Colorado. These mountain homesites often require individual wells and sewage disposal systems. Because many of the privately owned sewage disposal systems are poorly situated or improperly designed, wells and streams in the mountains are susceptible to contamination. Current federal regulations provide the principal constraints on design and construction of septic tank-leach field systems. These regulations are intended for use in regions where soil is six feet or more in thickness beneath the leach field area. Many of the individual sewage disposal systems now in operation in the Rocky Mountain region of Colorado are in technical violation of these federal regulations because of unsuitable soil conditions.

The mountain homesites are usually characterized by exposures of bare rock and areas of thin or discontinuous soil. This condition permits water and any contaminants which are present to directly enter fractures in the rocks. The filtering and purification of leach field waters can occur where soil or similar material receives the effluent, but the fractured crystalline rocks which underlie many mountainous areas do not effectively filter the percolating effluent. In addition, the rate and direction of contaminant movement through fractured rock may be difficult to identify. Therefore, the location of a leach field on a tract of land may be critical if contamination of well water is to be avoided. Current procedures, however, base selection of a leach field site largely on topographic and convenience factors. Where the subsurface consists of fractured crystalline rock, this is not a satisfactory practice. It should be clearly understood that the rule of thumb which calls for placement of a leach field downslope from a water well does not provide much insurance against contamination of the well water in mountainous terrain.

Investigations of over 100 homesites in the Rocky Mountains of north-central Colorado indicate that contamination of water wells may be decreased significantly where geologic conditions are considered in the selection of sites for leach fields and wells. Two separate but related field studies in Precambrian igneous and metamorphic terrain, supported by the Office of Water Resources Research, have provided data which illuminate the role of geologic conditions in the travel of ground water and contaminants in fractured media.

DISCRIMINANT FUNCTION ANALYSIS

In the first study (Freethey, 1969), 28 mountain homesites in north-central Colorado were selected for detailed analysis of variables thought to be related to pollution potential. See Figure 1 for general locations of study sites. The homesites were separated into two groups: the contaminated sites (Group I) consist of homesites where contamination of the well water can be documented and a pollution source can be identified; the uncontaminated sites (Group II) consist of homesites where no contamination can be detected but where a pollution source is present. Placement of a particular homesite into either Group I or Group II was done on the basis of a water quality test for *Escherichia coli* bacteria. Seven of the twenty eight sites studied had wells which were contaminated with *E. coli* bacteria.

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

[b] Assistant Professor, Department of Geology, Colorado State University, Fort Collins, Colorado 80521.

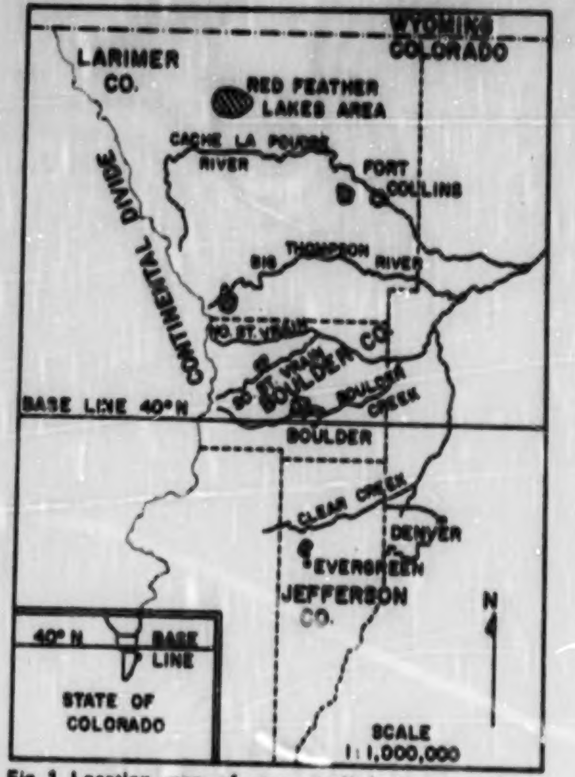
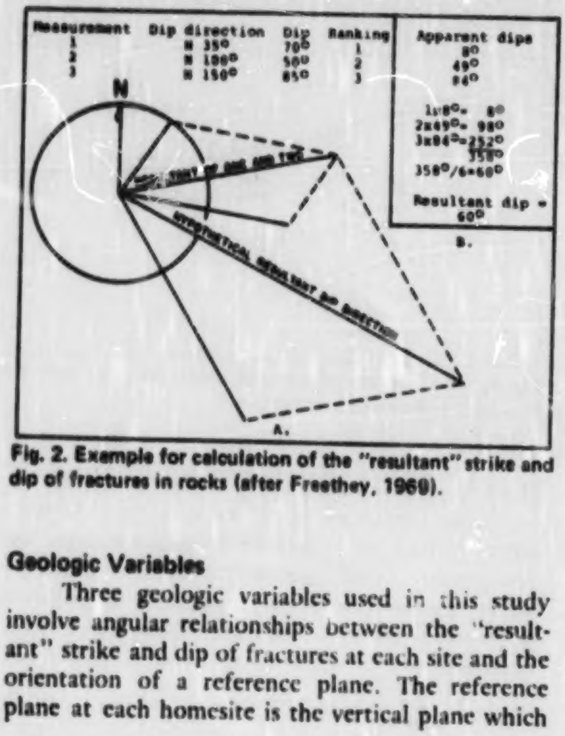

WYOMING
COLORADO
LARIMER CO.
RED FEATHER LAKES AREA
CACHE LA POUDRE RIVER
FORT COLLINS
CONTINENTAL DIVIDE
BIG THOMPSON RIVER
NO ST. VRAIN
SO ST. VRAIN
BOULDER CO.
BOULDER CREEK
BASE LINE 40° N
BOULDER
CLEAR CREEK
DENVER
EVERGREEN
JEFFERSON CO.
N
40° N
BASE LINE
STATE OF COLORADO
SCALE
1:1,000,000

Fig. 1. Location map of areas studied. Areas are crosshatched.

Selection of Variables

Quantitative measures of geologic, topographic, and hydrologic variables were collected at each homesite.

Geologic variables were devised to show the probable direction of effluent movement in relation to the position of the leach field and the well. Field data included measurements of the strike and dip of all major joint sets, foliation directions, and other fractures. These data were combined to obtain a "resultant" strike and dip which could be used as an approximation of the direction in which fluids would move through the unsaturated fractured media. To take into account the effects of spacing and width of fractures on permeability, a weighting procedure was devised by which fracture sets which appeared to be relatively impermeable would be assigned a ranking of one and fracture sets which appeared to have high permeability would be assigned a ranking of five. Fractures which appeared to have a moderate permeability were assigned rankings of two, three or four depending on their apparent permeability. The "resultant" dip direction is obtained graphically using the rankings given to each measurement. Figure 2 shows an example of this procedure. The vector which represents the first measurement with a ranking of one is drawn only half as long as the vector for the second measurement, which has a ranking of two. After the resultant of one and two is obtained, vector number three is drawn, which because of its ranking of three, is three times as long as number one. The final resultant dip direction is obtained by drawing another parallelogram, the sides being measurement three and the resultant of measurements one and two. The dip angles of each of the original surfaces are then projected onto the vertical plane of the hypothetical resultant dip direction. These apparent dips can be quickly determined with the use of a special protractor (Lahee, 1952). The apparent dips are then averaged according to their rankings, and a hypothetical resultant dip angle is obtained. This procedure is shown in part B of Figure 2.



Measurement	Dip direction	Dip	Ranking
1	N 35°	70°	1
2	N 100°	50°	2
3	N 150°	85°	3

Apparent dips
8°
49°
84°
1x8°= 8°
2x49°= 98°
3x84°=252°
358°
358°/6=60°
Resultant dip = 60°
B.
N
RESULTANT OF ONE AND TWO
HYPOTHETICAL RESULTANT DIP DIRECTION
A.

Fig. 2. Example for calculation of the "resultant" strike and dip of fractures in rocks (after Freethey, 1969).

Geologic Variables

Three geologic variables used in this study involve angular relationships between the "resultant" strike and dip of fractures at each site and the orientation of a reference plane. The reference plane at each homesite is the vertical plane which passes through the leach field and the well. Figure 3 illustrates the geologic variables. A description of the variables follows:

Variable #1. Angle between the azimuths of the "resultant" dip and the leach field-well plane.

Variable #2. Acute angle between the azimuths of the "resultant" strike and the leach field-well plane.

Variable #3. Vertical angle between the line connecting the leach field with the water level in the well and the projection of the "resultant" dip onto the leach field-well plane.

Variable #4. Degree of rock weathering. (Because weathered rocks may be effective in filtering and cleansing leach field effluent, some assessment of this variable was considered essential in evaluation of pollution potential at mountain homesites. A ranking procedure was devised. A rank of one represents relatively unweathered rocks, a rank of five represents a highly weathered rock mass.)

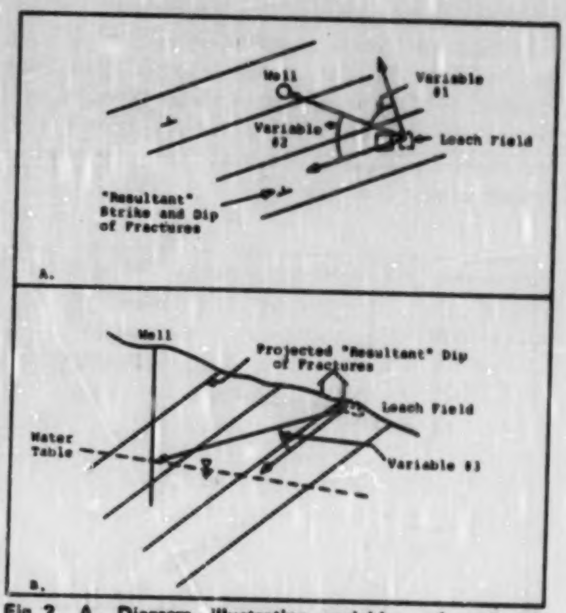

Well
Variable #1
Variable #2
Leach Field
"Resultant" Strike and Dip of Fractures
A.
Well
Projected "Resultant" Dip of Fractures
Leach Field
Water Table
Variable #3
B.

Fig. 3. A. Diagram illustrating variables #1 and #2; B. Diagram illustrating variable #3.

Hydrologic and Topographic Variables

The remaining variables used in this study were devised to represent those hydrologic and topographic conditions at the various homesites which are considered to be related to pollution potential. Figure 4 illustrates these variables. A description of the variables follows:

Variable #5. Angle between the azimuths of the water table gradient and the leach field-well plane. (In several cases the azimuth of the water table gradient was estimated from land surface topography.)

Variable #6. Depth to static water level in the well.

Variable #7. Vertical angle between the well head and the leach field.

Variable #8. Angle between the azimuths of the topographic gradient in the immediate vicinity of the leach field and the leach field-well plane.

Variable #9. Magnitude of the topographic gradient at the leach field as projected onto the leach field-well plane.

Variable #10. Horizontal distance between the well and the center of the leach field.

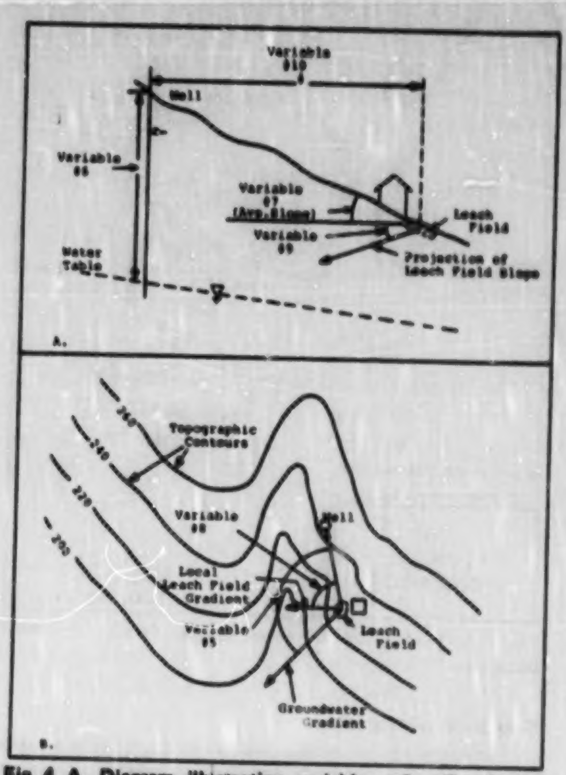

Variable #10
Well
Variable #6
Variable #7 (Avg. Slope)
Variable #9
Leach Field
Projection of Leach Field Slope
Water Table
A.
260
240
220
200
Topographic Contours
Variable #8
Well
Local Leach Field Gradient
Variable #5
Leach Field
Groundwater Gradient
B.

Fig. 4. A. Diagram illustrating variables #6, #7, #9, and #10; B. Diagram illustrating variables #5 and #8.

Statistical Analysis

A discriminant function analysis was done to determine if any of the ten variables used were related to or sensitive to the incidence of pollution. Briefly, the discriminant function analysis is a standard statistical technique which computes a linear function of n variables measured on each individual of two groups. This linear function provides a criterion for discrimination between the groups. The function is computed so that the difference between the mean indices for the two groups divided by their pooled standard deviation should be as large as possible. Fisher (1946) discusses the computational steps and data requirements for the discriminant function analysis.

Results of Discriminant Function Analysis

The two most significant variables were variable • 1 (angle between the azimuths of the "resultant" dip and the leach field-well plane) and variable • 8 (angle between the azimuths of the topographic gradient at the leach field and the leach field-well plane). The significance of variable • 1 apparently stems from the tendency of leach field effluent to follow the dip of fractures in the zone of aeration. The significance of variable • 8 is possibly due to the tendency for near surface fluids to percolate laterally down slope in response to gravity and zonation of weathering. If lateral movement of effluent from the leach field has a component toward the well, pollution potential is increased.

Using only variables • 1 and • 8, a discriminant function significant at the 0.1% level was obtained. The values of the discriminant function for all 28 sites are given in Table 1. Values of the discriminant function are computed using the following formula:

$$D(f) = -.00196(V_1) - .0015(V_8)$$

where D(f) is the discriminant function, V_1 is the value for variable one, and V_8 is the value for variable eight. The discriminant function D(f) can be calculated for a site if estimates can be obtained for variables • 1 and • 8.

Table 1. Discriminant Function Values
(after Frothey, 1969)

Rank	*Values for polluted group*	*Values for unpolluted group*	*Polluted site no.*	*Unpolluted site no.*
1	-.09678		5	
2	-.12491		2	
3	-.14253		3	
4	-.18165		1	
5		-.22372		20
6		-.24201		18
7	-.24230		4	
8		-.28114		19
9		-.28536		21
10	-.29549		6	
11		-.30788		12
12		-.32189		13
13	-.35614		7	
14		-.36201		17
15		-.37507		10
16		-.37766		6
17		-.38321		3
18		-.39665		14
19		-.40115		15
20		-.40573		11
21		-.41615		8
22		-.41615		9
23		-.41714		2
24		-.42856		16
25		-.44093		7
26		-.46410		1
27		-.48433		4
28		-.51041		5

FLOW FIELD DIAGRAM METHOD

The second study (Millon, 1970) included 85 mountain homesites in the Red Feather Lakes Area, Larimer County, Colorado (see Figure 1). Sixty two percent of the wells tested at these homesites were found to be contaminated with *E. coli* bacteria. Data collected for 65 well sites established the position of each well relative to the nearest leach field. Data were also collected on the orientation of bedrock jointing surfaces and on water levels in wells so that ground-water flow directions could be evaluated. Figure 5 shows contours drawn on water level elevations in wells. The study area was divided into 9 subareas in order to obtain a single generalized direction for the hydraulic gradient in each of the subareas. The generalized directions of the hydraulic gradient are indicated by the wide arrows in Figure 5. Orientations of major high angle joints in the Red Feather Lakes Area are summarized in Figure 6. The ground-water flow pattern at any point in the area was assumed to be determined by the combined effects of the hydraulic gradient and the orientations of both major and minor jointing surfaces in the rock.

The data on well and leach field locations, joint orientations, and ground-water flow potential were all combined by means of a specialized "flow field" diagram (see Figure 7). This diagram is intended to graphically illustrate how bedrock fracture orientations may affect transport of leach field effluent by ground water. A region of high pollution potential can be identified on the flow field diagram.

Results

The study showed that wells in the Red Feather Lakes Area which, because of their position relative to nearby leach fields, plot on the flow field diagram within the region of high pollution potential have about four times the incidence of pollution as do wells which plot outside the region.

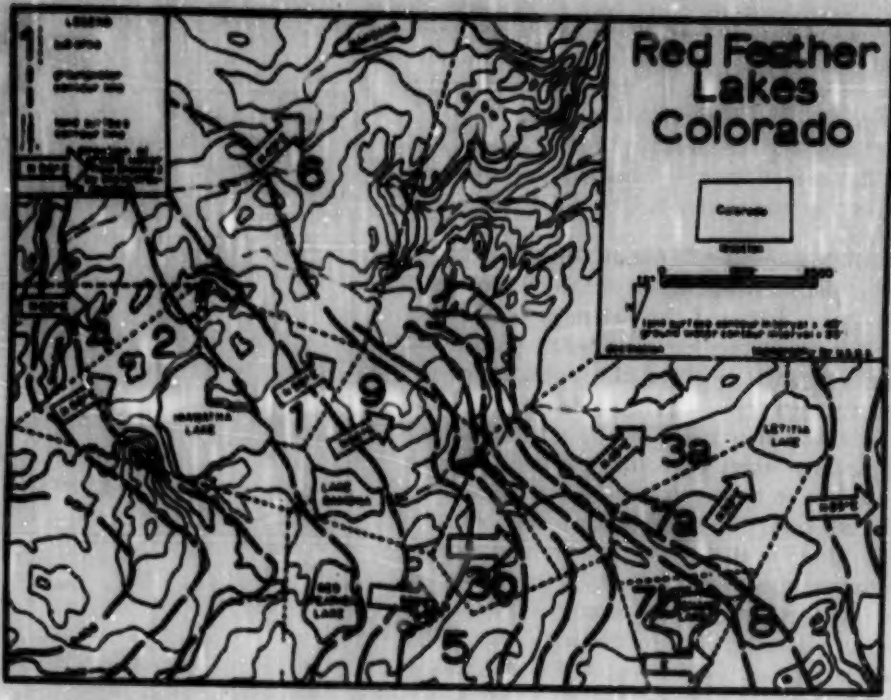

Red Feather Lakes Colorado
LEGEND
Colorado
6
2
4
1
9
3a
7a
3b
5
8
LAKE HIAWATHA
LETITIA LAKE
RED FEATHER LAKE

Fig. 5. Map showing subareas and hydraulic gradients for the Red Feather Lakes Area (after Millon, 1970).

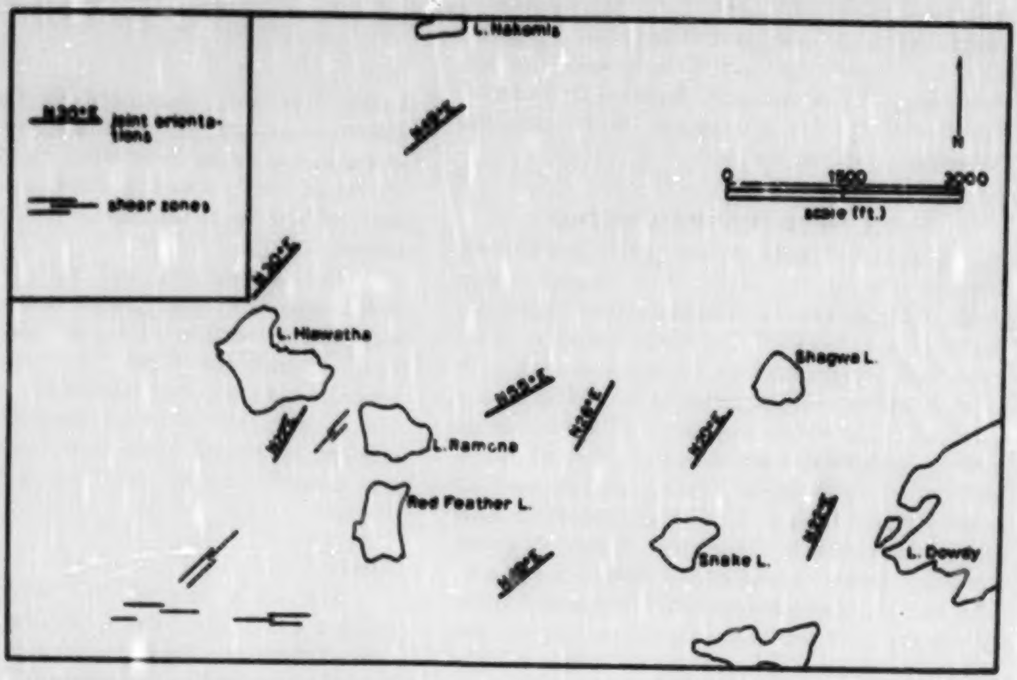

L. Nakomis
N30°E joint orientations
shear zones
N
0
1000
2000
scale (ft.)
L. Hiawatha
Shagwa L.
L. Ramona
Red Feather L.
Snake L.
L. Dowdy

Fig. 6. Map of Red Feather Lakes Area showing generalized orientations for major joints and shear zones (after Millon, 1970).

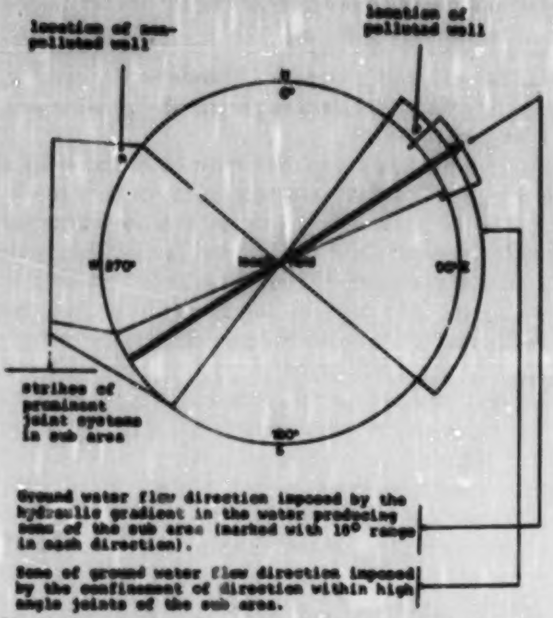

location of non-polluted well
location of polluted well
N
0°
W 270°
90° E
180°
S
strikes of prominent joint systems in sub area
Ground water flow direction imposed by the hydraulic gradient in the water producing zone of the sub area (marked with 10° range in each direction).
Zone of ground water flow direction imposed by the confinement of direction within high angle joints of the sub area.

Fig. 7. Hypothetical flow field diagram showing locations of wells in relation to neighboring leach fields (after Millon, 1970).

A normalized significance test employing Bernoulli data (i.e., the percentage of polluted wells in the flow field and the percentage of nonpolluted wells in the flow field) was of the following form:

$$t = \frac{\hat{\pi}_p - \hat{\pi}_u}{\sqrt{\hat{\pi}_T(1-\hat{\pi}_T)\ [\frac{1}{N_1} + \frac{1}{N_2}\ ]}} = 2.31$$

where

$$\hat{\pi}_p = \frac{\text{number of polluted wells in flow field}}{\text{total number of polluted wells}} = \frac{25}{45} = .555$$

$$\hat{\pi}_T = \frac{\text{total number of wells in flow field}}{\text{total number of wells}} = \frac{30}{65} = .462$$

$$\hat{\pi}_u = \frac{\text{total number of nonpolluted wells in flow field}}{\text{total number of nonpolluted wells}}$$

$$= \frac{5}{20} = .25$$

N_1 = number of nonpolluted wells = 20

N_2 = number of polluted wells = 45.

The "t" value obtained by the above formula showed statistical significance at the one percent level.

CONCLUSIONS

The analyses which have been described can be reliable only if geologic conditions are adequately represented. A hidden fault or igneous dike can invalidate a site evaluation based on the discriminant function or flow field criteria. Hence, these methods for evaluating pollution potential at mountain homesites should be considered reliable only in the statistical sense. Much additional data must be acquired before an acceptable criterion for evaluation of pollution potential can be developed.

Although results of these two studies should be considered preliminary, they do tend to confirm that the orientation of jointing surfaces in the bedrock does affect the travel path of contaminants. Thus, evaluation of pollution potential at mountain homesites similar to those investigated in these studies must include detailed geologic analysis of bedrock underlying the thin soils.

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Lahee, F. H. 1952. Field geology. McGraw-Hill Book Co., New York, Appendix 14, 583 pp.

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DISCUSSION

The following questions were answered by James P. Waltz after delivering his talk entitled "Methods of Geologic Evaluation of Pollution Potential at Mountain Homesites."

Q. *What is the range of values of the diversion radius of the well compared to the distance between well and waste disposal sites?*

A. The problem of proper spacing between leach fields and wells is a very real one. I showed a diagram which illustrated that fluid can travel from the leach field toward the well along fractures in the zone of aeration. I showed another portion of the diagram which demonstrated that local topographic reverses might cause percolating fluids to enter the ground water upstream of the well because the regional ground-water gradient is different from the local topographic slope. There is also the very common problem, which the questioner has raised, where the leach field is at the ground surface and is recharging the ground water while the well is perhaps 200 feet away pumping water and creating a large cone of depression in the ground water around the well. This condition reverses the ground-water gradient so that even if the well was originally upslope both topographically and with respect to the ground-water gradient the flow direction can change very quickly.

I don't have any figures for the shape and size of the drawdown cone. It will probably be a while before we know very much about that. The problem can be approached on a theoretical basis, assuming fractures are like parallel plates. We've done some experimenting with this type of model to determine the interaction between a series of wells and a series of leach fields as, for example, would occur in a subdivision. The results from this type of analysis are useful but fairly generalized. The fact of large diversion radii of mountain wells certainly contributes to the pollution potential because the storage capability of fractured crystalline rocks is minuscule compared to most aquifers. We're talking about less than 1% porosity, even in fairly fractured rock. Tremendous drawdowns are associated with the withdrawal of water and this certainly is going to affect the direction of ground-water flow in the vicinity of the well.

Q. *Are there E. coli in the lakes and streams of the Red Feather Lakes Area?*
A. Yes.

Q. *What were their percolation rates?*
A. The percolation rates vary tremendously. Even within an individual half acre or acre lot it is possible to get a wide range of percolation rates.

Q. *Were the contaminated wells evaluated for sanitary construction?*
A. No, the homesites that we checked were homesites which had been in operation for quite some time, and we assumed that the wells were in a state of equilibrium with their environment, including the nearby leach field. I think that in some cases there might have been poor construction practices associated with the contamination.

Q. *Was any attempt made to clean up the contaminated wells with chlorine?*
A. Certainly. Many of the people in these areas that we studied have gone to chlorination systems. This is one certain way they can fight the problem. We had to make special arrangements to obtain our samples from their nonchlorinated supply. We sometimes tapped into their water system upstream from the chlorination.

Q. *Were tests run for other enteric bacteria?*
A. There was a facet of our study done by our microbiologist which included additional testing but no extensive program of testing has been done other than on the *E. coli.*

Q. *Do you believe values of variables V-1 and V-8 can be reliably obtained in the vicinity of most new homesites?*
A. Data for these variables must be collected by a geologist. The data collection presents an interesting problem because many of the homesites are built on somewhat flat ground where thin soils commonly obscure the bedrock. It is necessary to go to the periphery of the homesite to find the rocks that are in place where orientations of fracture systems can be recorded. We usually would measure at least several dozen fracture orientations to establish the uniformity of these fractures throughout the homesite area. Where we could do this, I feel the measures are reliable, but in some cases we had exposures on maybe only 2 or 3 sides of the property. In these cases there is room for all sorts of geologic features which can invalidate the criterion. As I have said, we're hoping here only for the statistical validity. There is no absolute security in the discriminant function criterion because there are often going to be complicating geologic factors.

Q. *How do you evaluate the reliability of a relatively variable discriminant function?*
A. We hope to evaluate this discriminant function after we have extended the data base to include a large number of sites. Then we wish to apply it to a number of unknown sites and test the success of our classification. I think this can be done. Reliability can be tested in a statistical sense. The discriminant function is variable because of the nature of the function. If it were not highly variable then its value as a classification criterion would be less.

Q. *Why not simply require a chemical home treatment system where there is less than 6 feet of soil?*
A. Economics appears to be the main reason. However, there must be alternatives to the septic tank leach field system in these areas where there is an inadequate soil. Here in Colorado, the Water Pollution Control Commission has issued new rules on septic tank practices which include the "designation" of pollution prone areas in the State. For these "designated" areas, special engineering and geologic studies will be required before approvals for private sewage disposal systems can be obtained. It looks to me like this is a great step forward. What it will likely mean is that a detailed investigation will show that a septic tank system cannot be installed in most areas and alternative systems will have to be considered. I'm not a sanitary engineer and I don't know about the

success of many of these chemical systems. I have heard that many of the present alternatives to septic tank systems are not entirely reliable because they require a degree of maintenance which is often lacking. The leach field system has worked beautifully where conditions are appropriate because it doesn't really need much maintenance.

Q. *Do you have any minimal lot size regulation for lots in Precambrian crystalline rocks where both wells and septic tanks are used?*

A. In order to assess the minimum size of lots from mountain homesites we need to know a little more about what happens to the bacteria that enter the fracture bedrock. We know that they can easily travel hundreds of feet, and we may even be talking about travel of ¼ of a mile or more without being appreciably filtered out or absorbed. We are presently involved in studies where we've taken different rock types, crushed them, sized them, and added water containing known quantities of *E. coli.* The fluids were periodically tested for two weeks to determine a die-off curve for *E. coli.* We found remarkable variations in the chemical effect of the rocks on the viability of the organisms. I think this sort of data will ultimately be useable in determining minimum lot sizes for various types of geological terrain. We have also attempted to learn a little more about the rate of travel of fluids through crystalline rocks, because in addition to the time that is required to kill off these organisms in the rock you must be concerned about how fast the fluid is going to move in that period of time. These data are necessary to determine what the safe radius from a leach field is going to be. So we have taken areas such as the road cut shown in this picture, where well defined joint sets can be seen, and injected fluids into the rock fractures. We put 55 gallon drums filled with bacteria-inoculated water at the top of the cliff and siphoned the fluid into PVC pipe that had been cemented into the rock. In this case the bacteria-laden water surfaced down here at approximately 15 to 20 feet away from the injection point. I just wanted to show that we get effluent coming out of this rock, this highly fractured rock concentrated at this location. We were able to collect the fluid and sample the bacteria. We found that essentially nothing was filtered out. The same concentrations were at the bottom as at the top. Little seeps occurred at 3 or 4 other places, but this was the only place where any real flow occurred and the rate was quite high. We had a garden hose, and as fast as it would siphon, the fluid would go into the rock.

Q. *Who is working on development of a better septic tank system?*

A. I have nothing more to say about alternatives. I know there are lots of people who recognize that the septic tank needs to be improved or replaced for installations in mountainous areas. I am confident that there are better solutions presently available and that they will be used only if the pressure is put on people to not use septic tank-leach field systems any more where terrain is not suitable. We just have to cut them off.

Q. *Here's a question about your testing methods for E. coli. Do you mean coliform by standard method? What technique did you use for E. coli analysis? Did you run any tests for fecal coliform since these are a better indicator of domestic sewage contamination?*

A. I wish I had the microbiologist associated with this project here to answer that question. We, for the studies I've recorded here, did test only for the *E. coli.* We considered a site to be contaminated if large numbers of *E. coli* were present in the water samples taken. We did find variations in the content of *E. coli* in the samples we obtained. We took several samples at each site and replicate determinations were made. We went back on different days, different weeks, and in some cases as many as a dozen or more samples were repeated so that we were relatively sure of the status of contamination. And, in some cases, definitely contaminated wells would be retested and turn out to be okay. We tried to tie this in with precipitation patterns and a number of other things. There are obviously a number of factors which influence the changes with time in the concentration of *E. coli* in ground water.

Nitrate in Ground Water of the Fresno-Clovis Metropolitan Area, California[a]

by Kenneth D. Schmidt[b]
Member NWWA

ABSTRACT

Natural concentrations of nitrate are quite low in most ground waters in the eastern part of the San Joaquin Valley. High nitrate contents are related to sewage effluent percolation ponds, septic tank disposal systems, industrial waste-waters, and agricultural fertilizers. Hydrologic factors are closely related to the occurrence of nitrate. Transmissibility of the aquifer, hardpan development in the soil, canal recharge, and cobble zones in the subsurface are the primary factors of importance. Nitrate is stratified in the aquifer beneath unsewered metropolitan areas and highest contents occur in the upper 50 or 60 feet. Water quality hydrographs were used to show long- and short-term trends in nitrate. Chloride and nitrate hydrographs, trilinear diagrams, the distribution of other constituents, and hydrologic data were used to effectively delineate sources of nitrate in areas where numerous potential sources were present. Conclusions from ground-water data agree well with previous studies in other areas beneath unsewered tracts and near sewage treatment plants in which attention was focused primarily on the soil or the unsaturated zone.

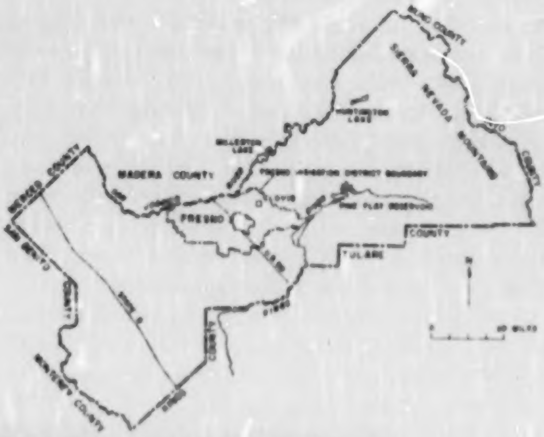

Fig. 1. Fresno County and related features.

INTRODUCTION

Fresno County was formed in 1856 out of the Mariposa territory and currently produces the greatest amount of agricultural wealth of any county in the nation. The Fresno Irrigation District (Figure 1) supplies surface water to much of the agricultural area through canals from the Kings River, which drains part of the Sierra Nevada east of Fresno. The Fresno-Clovis Metropolitan Area (F.C.M.A.) comprises about 145 square miles between the Kings and San Joaquin Rivers in the east-central portion of the San Joaquin Valley. Rapid industrial growth has occurred in the past decade and population of the urban area reached 310,000 in 1969.

Water for municipal and industrial use is pumped from wells, whereas in the surrounding agricultural area surface water and ground water are used. Ground water occurs in the alluvial-fan deposits derived from the Sierra Nevada. The principal subsurface geologic units were divided into consolidated and unconsolidated materials by Page and LeBlanc (1969). Consolidated rocks comprise the basement complex of pre-Tertiary age and the marine and continental rocks of Cretaceous and Tertiary age. The basement complex is about 3,000 feet deep beneath Fresno. Unconsolidated deposits are the major source of ground water pumped by wells in the Fresno area. Deposits of Quaternary age crop out over most of the area and comprise the principal aquifer. These deposits include numerous intercalated strata of sand, gravel, silt, sandy clay, clay, and localized cobble zones. Most of the ground water moves laterally in coarse-grained beds, and the vertical movement of water is restricted in places by thick layers of clay and silty clay.

The climate of the F.C.M.A. is characterized by a long, warm, and dry summer from May through October, and a cool, rainy winter season from November through April. Annual precipitation at Fresno averages about eleven inches. The amount of precipitation in the foothills and mountains of the Sierra Nevada directly affects the streamflow, recharge to ground water, and surface water supply. Much of the precipitation at higher elevations falls as snow, and runoff in major streams usually reaches a peak in June or July, following periods of high snowmelt.

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[a] Presented at the National Ground Water Quality Symposium, August 25-27, 1971.

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Depth of ground water averages about 70 feet beneath the F.C.M.A., and the regional direction of flow is southwest. A ground-water cone of depression exists beneath part of the urban area due to large pumping extractions. Sources of recharge include seepage from streams and canals and ground-water inflow from the east. Well depths range from less than 100 to more than 500 feet. Most wells were drilled by the cable-tool method until recently, and unperforated casings were installed with open bottoms. Recently, wells have been drilled by the reverse-rotary method and gravel packed. The average specific capacity is about 130 gallons per minute per foot (gpm/ft) and the average transmissibility exceeds 220,000 gallons per day per foot (gpd/ft).

A detailed correlation of subsurface rock types was made as part of the development of the lithologic framework of the area. Drillers' logs were correlated with several electric logs available. Extensive deposits of cobbles and coarse sands occur to depths greater than 500 feet in the northern portion of the F.C.M.A. An impermeable hardpan of the San Joaquin Series also occurs over much of the northern part of the area. Other soils vary in hardpan development and the Madera sand has virtually no hardpan development. Correlations generally suggested little continuity of clay strata, but some cobble zones were traced for several miles. Clays predominate below 350 to 400 feet depth in the southern portion of the F.C.M.A. The depth of Quaternary alluvium ranges from 350 to 400 feet, and the underlying continental deposits are finer grained except near the major rivers.

High nitrate in drinking water is important because of an infant disease, methemoglobinemia. Concentrations exceeding the 1962 U. S. Public Health Service limit of 45 parts per million (ppm) were noted in the F.C.M.A. by the California Department of Water Resources (1965). The primary sources of ground-water nitrate were identified as sewage effluent percolation ponds at the Fresno Sewage Treatment Plant and septic tank disposal systems in unsewered areas. Nitrate concentrations ranged from 0.8 to 58.5 ppm, and averaged 15.1 ppm, for the F.C.M.A. Most high nitrate contents were from samples collected from shallow wells. Analyses of surface waters showed low concentrations of all constituents, including nitrate. Analyses of wastewaters at sewage treatment plants, wineries on independent disposal systems, and a meat-packing plant were presented. Although high concentrations of most constituents were apparent, total nitrogen was generally unreported.

Behnke and Haskell (1968) studied nitrate in ground water near the Fresno Air Terminal. They noted the importance of septic tanks and the Clovis Sewage Treatment Plant as nitrate sources. Nightingale (1970) reported on the salinity and nitrate trends for ground water of the urban area and the surrounding agricultural lands. Although urban zone well water nitrate was almost twice that of the agricultural zone for the period 1950-56, for the period 1962-67 the two zones had an almost equivalent nitrate content. The mean nitrate content of the agricultural zone well water increased by 300 percent from year lot 1950-56 to year lot 1962-67, but no reason for this increase was given.

Despite these studies and others, many questions have remained unanswered with regard to ground-water nitrate in the F.C.M.A. Questions as to source, effect of lithology and well construction on nitrate, and relation to the hydrologic system often have arisen. It is my intent to establish a firm hydrologic framework for the present study. A model can be built upon this framework to describe the sources and distribution of nitrate in ground water of the F.C.M.A.

Five sites were selected for detailed analysis (Figure 2). The Figarden-Bullard Area was selected because of the prevalence of one nitrate source, namely septic tank effluent. A second site selected was the vicinity of the Fresno Sewage Treatment Plant, which comprises the majority of sewage treatment on a volume basis in the F.C.M.A. Sewage effluent disposed of by percolation ponds is the primary nitrate source to ground water in this area. The Tarpey Village and Mayfair-Fresno Air Terminal Areas are both unsewered and have

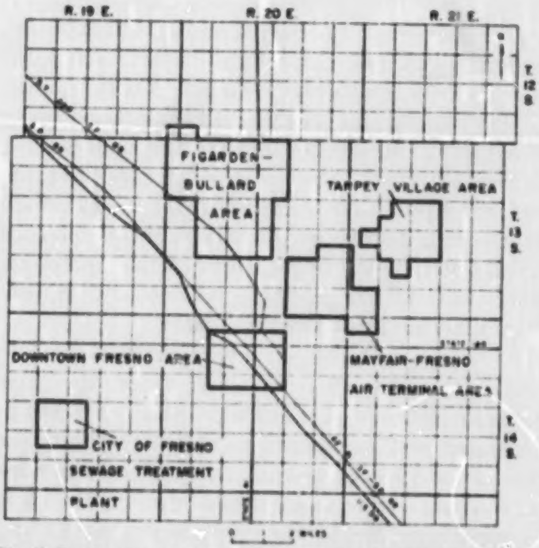

Fig. 2. Study areas in the Fresno-Clovis Metropolitan Area.

some of the highest nitrate contents reported in the F.C.M.A. Sources other than septic tanks are present, including sewage effluent percolation ponds, winery wastewater disposal ponds, and agricultural fertilizers. The fifth study site comprised the Downtown Fresno area, which is sewered and has no obvious nitrate source. Although high nitrate contents have been monitored by several wells in this area, virtually no study had previously been undertaken.

FIGARDEN-BULLARD AREA

Schroepfer and Polta (1969) reported on nitrate in ground water of septic tank areas near Minneapolis and related ground-water contamination to suburban growth. These authors found that septic tank effluent had an average ammonia-nitrogen content of 28 ppm or 123 ppm nitrate equivalent. The Figarden-Bullard Area is in the northern part of the F.C.M.A. Although the area is unsewered, only three wells have ever had nitrate over 25 ppm. Ground-water depth ranges from 90 to 100 feet and water levels have declined about 2 or 3 feet per year for the past decade. Lithologic sections show an abundance of hardpan, sand, and cobble zones in this area. Much of the hardpan is impermeable and is in the San Joaquin sandy loam soil type. About 80 or 90 percent of the area was agricultural in 1950, whereas less than 20 percent was agricultural by 1970. Population density is lower than for most other urban parts of the F.C.M.A.

Chemical hydrographs were prepared to illustrate long- and short-term trends in water quality. The predominant historical trend in the northern portion of the Figarden-Bullard Area was constancy of nitrate. This portion has the largest transmissibilities, the most abundant cobble zones, and the greatest development of impermeable hardpan in the Figarden-Bullard Area. About one-half of the hydrographs in the southern portion had a constant nitrate trend, whereas the remainder had increasing trends. The southern portion had the earliest septic tank development and maximum septic tank density of the area. Cobble zones are locally absent, transmissibilities of the aquifer are lower than in the northern portion, and the impermeable hardpan is locally missing.

Nitrate and chloride hydrographs (Figure 3) were drawn for all wells where more than four separate analyses were available. Short-term trends indicated similar nitrate and chloride patterns for 16 out of 19 hydrographs. This similarity prevails throughout septic tank parts of the F.C.M.A. and is apparently due to the derivation of nitrate and chloride from septic tank effluent and the mobility of both ions in ground water. Three hydrographs with opposite nitrate and chloride short-term trends were for wells apparently affected by sewage effluent from plants north of the Figarden-Bullard Area.

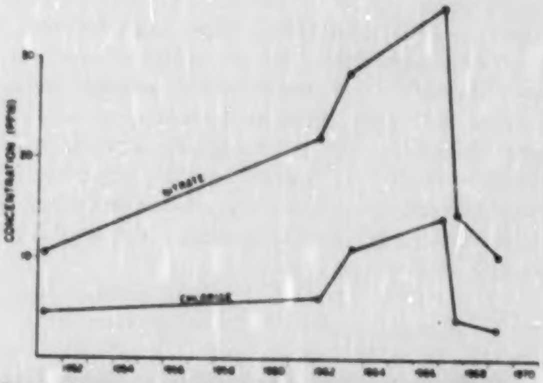

Fig. 3. Nitrate and chloride hydrographs for a selected well.

Water samples from wells have been taken semiannually for nitrate analysis in several Fresno County Waterworks Districts in the Figarden-Bullard Area. Nine wells had greater nitrate contents in the summer than in the winter, and had cased depths less than 150 feet. Higher nitrate contents in the summer are due to downward movement of shallow waters, which are high in nitrate, to producing zones during heavy pumping. Higher temperatures in the summer also favor nitrification of ammonia-nitrogen retained in the soil from septic tank effluent. Five wells had higher nitrate contents in the winter than in the summer, and had cased depths greater than 150 feet. This group of wells was on canal banks or nearby. Low nitrate contents in the summer are attributable to canal dilution by low nitrate Kings River water, as several major unlined canals traverse the area. Low nitrate contents in the summer occur for wells where the impermeable hardpan is absent throughout the F.C.M.A.

The concept that nitrate is stratified in the aquifer was tested in the Figarden-Bullard Area. Only open-bottom wells were used in this analysis, as they tend to draw water from specific portions of the aquifer. The difference between depth to water and cased depth is a reflection of the amount of aquifer penetrated and is generally related to the zone of production. Depth to water was taken from the Fresno Irrigation District Map for December, 1970. The difference between depth to water and cased depth is referred to herein as "aquifer penetration," and values for specific wells were plotted graphically with 1970 nitrate analyses (Figure 4).

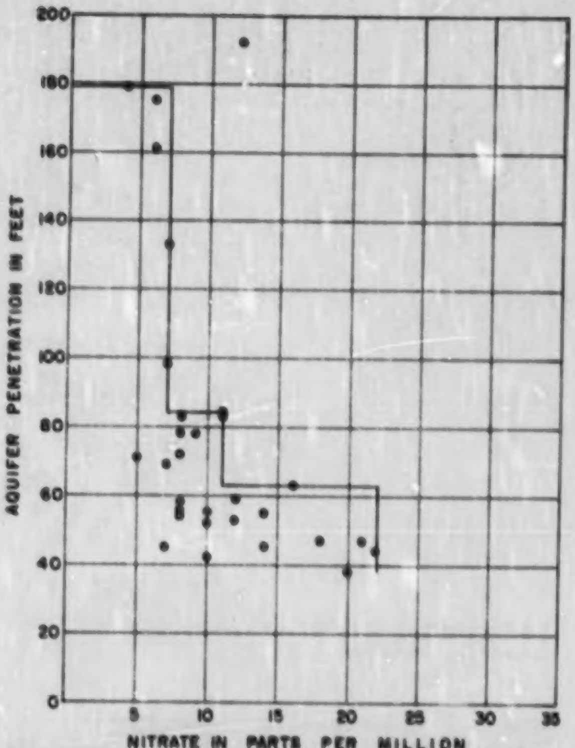

Fig. 4. Relation between aquifer penetration and 1970 nitrate for wells in Figarden-Bullard Area.

The number of wells with low nitrate contents in each major depth zone shows that there is no continuous "nitrate cap" in the Figarden-Bullard Area, a fact also shown by contours drawn for nitrate content on an areal basis. The highest nitrate contents are in the upper 60 feet of the aquifer, and about 5 to 7 ppm approximates the "background" nitrate in the ground water. The decrease in nitrate content with depth in the upper 80 feet of the aquifer averages about 1 ppm per 4 feet of depth. Wells with the highest nitrate contents for their specific aquifer penetration were usually within the zone of lowest transmissibility and in the area where septic tanks had been used for the longest time.

The low nitrate contents in the aquifer of the Figarden-Bullard Area are attributed in large part to hydrogeologic factors. Extensive cobble zones permit more dilution and dispersion of high nitrate recharge from septic tank disposal systems. Few wells are extremely shallow or perforated in shallow intervals, and the water table is relatively deep. The presence of an impermeable hardpan prevents percolation of nitrogen forms in some cases, unless it is penetrated by leach lines or seepage pits from septic tanks. The low density of septic tanks compared to other unsewered areas of the F.C.M.A. has also minimized nitrate contents. Although the Figarden-Bullard Area was converted from primarily an agricultural area in 1950 to an urban area at present, there is little evidence of greatly increasing nitrate contents. Little downgradient movement of nitrate from septic tank areas to sewered areas has occurred. The Figarden-Bullard Area is perhaps the ideal location in the F.C.M.A. for operation of septic tank disposal systems. With proper construction of wells and septic tank disposal systems, little problem with high nitrate contents in ground water should occur in the future.

FRESNO SEWAGE TREATMENT PLANT

The Fresno Sewage Treatment Plant is about 3 miles southwest of downtown Fresno and has been in operation since 1891. Plant No. 1 has provided primary treatment since 1947 and Plant No. 2, which was built in 1960, provides secondary treatment. Final disposal of most of the effluent is by percolation on 1,440 acres of ponds. About 10 to 15 percent of the effluent is used for crop irrigation on nearby lands. Wastewater flow currently averages almost 30 million gallons per day. The total nitrogen in domestic wastewater effluents ranges from about 18 to 28 ppm when there is no specific treatment for nitrogen removal. Records at the Fresno Sewage Treatment Plant suggest that the average total nitrogen content is about 25 to 30 ppm, about 8 to 10 ppm of which is in the ammonia form. Nitrate contents averaged about 6 ppm in 1969. Although industries comprise only about 10 percent of the sewage influent to the plant, wineries contribute significantly to waste strengths during the period from September 1 to December 1.

Jenks and Adamson (1968) determined pond percolation rates and ground-water quality at the Fresno Sewage Treatment Plant. Eight auger holes were drilled to reach the ground water and water samples were collected. Five of the eight water samples had nitrate contents less than 4 ppm, whereas nitrate contents for the remaining samples were 76, 160, and 213 ppm. The holes with high nitrate content were in a newer area where ponds were periodically dried out in order to achieve higher infiltration rates. These holes were apparently in an area recently dry and just flooded. High nitrate water is common at the beginning of flooding cycles (Stout, Burau, and Allardice, 1965), and the water is readily leached to ground water. Ponds develop anaerobic conditions when kept full and nitrogen is retained in the soil in the organic and ammonia forms. Aerobic conditions develop when ponds are periodically dried out and nitrification can occur. Nitrate is then leached upon the next wetting of the ponds, and this period is followed by low nitrate recharge water once anaerobic conditions develop. Denitrification can also substantially reduce nitrate contents under anaerobic conditions.

Typical percolation pond water was sampled for a portion of 1968. Analyses for nitrate-nitrogen, ammonia-nitrogen, and pH demonstrate the influence of winery wastewater at the Fresno Sewage Treatment Plant. One pond had an average ammonia-nitrogen content of about 1.2 ppm prior to September 1, and an average of 8.5 ppm during the winery season of September 1 to December 1. The average ammonia-nitrogen content for another pond was 4.1 ppm prior to September 1, and 8.5 ppm during the winery season. Nitrate-nitrogen for the first pond during the same period increased from an average of 0.3 to 2.1 ppm. Nitrate-nitrogen for the second pond increased from 0.4 to 1.7 ppm for the same period. Winery wastewaters in the F.C.M.A. have a total nitrogen content ranging from 4 to 10 times that of typical domestic sewage effluent.

Chemical hydrographs were prepared for 6 monitor wells near the Fresno Sewage Treatment Plant. All hydrographs showed similar seasonal fluctuations (Figure 5) for nitrate and ammonia. Nitrate contents sharply decrease after maximum values in September. Contents gradually [illegible]ease to a minimum in March and gradually inc[illegible]e to July. Contents sharply increase in August and September. High nitrate contents occur in ground water at the beginning of the winery season, when the nitrogen contents of pond waters are very high. However, pond waters also have the highest biochemical oxygen demand for the entire year at this time. These highly anaerobic wastewaters readily utilize oxygen, and nitrification cannot occur. Nitrogen is thus regained in the soil and not leached to the ground water; hence ground-water nitrate content sharply decreases. Nitrification does not occur as rapidly during the winter and nitrate contents gradually decrease until the spring. Nitrification readily occurs with the warming temperatures of the spring and summer, nitrate is readily leached to ground water, and contents gradually increase to the fall. Maximum nitrate contents in the ground water each year may actually be due to nitrogen supplied to the soil during the previous year. Pond operation during the summer includes more drying out cycles, as the wastewater flow is smaller, and aerobic conditions tend to develop, which also favor nitrification. Waste flows are the largest in the winter and ponds are generally kept full, allowing anaerobic conditions to develop. The seasonal variation in nitrate (Figure 5) clearly indicates the inherent limitations of comparisons made from year to year based on only one analysis per year.

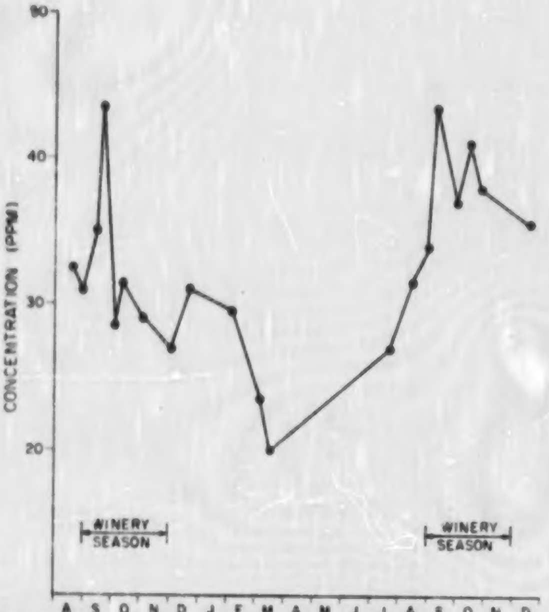

Fig. 5. Nitrate concentrations in ground water near Fresno Sewage Treatment Plant.

Ammonia-nitrogen contents of ground water show opposite trends to nitrate-nitrogen near the Fresno Sewage Treatment Plant. The highest contents occur in March and the lowest contents occur in September. The soil retains nitrogen on adsorptive and cation-exchange sites when little nitrification occurs. Ammonia gradually tends to be leached in small amounts as the capacity of the soil to retain nitrogen is approached. The ammonia contents of ground water are high when nitrate contents are low, because little nitrate is formed under these conditions. Much of the capacity of the soil to retain nitrogen is unused when abundant nitrification occurs, as much of the nitrogen is converted to nitrate and leached. Little ammonia is leached in this case, as it is either retained by the soil or converted to nitrate.

A number of chloride and nitrate hydrographs for wells near the Fresno Sewage Treatment Plant exhibit opposite nitrate and chloride short-term trends. That is, as the nitrate content increases for a period, the chloride content simultaneously decreases. This trend was thus in contrast to that observed in septic tank portions of the F.C.M.A. Chlorides are an effective tracer in ground water of the F.C.M.A., because natural concentrations are quite low. Ground water affected by sewage effluent generally has chloride concentrations exceeding

45 ppm. High chlorides in ground water near the treatment plant suggest that little dilution of sewage effluent occurs, a fact also suggested by the amount of water recharged on an annual basis. A trilinear diagram for various ground-water samples showed a consistent chemical type, with sulfate less than 10 percent and chloride ranging from 10 to 20 percent on a reacting value basis.

TARPEY VILLAGE AREA

Nitrate has substantially increased in ground water of the Tarpey Village Area (Figure 6) in the past, and there are a number of potential sources. Thirteen wells have had nitrate over 25 ppm at least once, and 6 of these wells have had nitrate over 45 ppm. Tarpey Village proper presently has municipal sewerage connections east of Clovis Avenue, whereas septic tanks are used west of Clovis Avenue. The area is bounded on the east and northeast by extensive acreages of vines, peaches, and pastures. Johnson et al. (1965) conducted a subsurface drainage study of the San Joaquin Valley. Variable portions of applied nitrogen in agricultural areas were lost with the drainage waters. The nitrogen content of drainage water ranged from 1.8 to 62.4 ppm, with a weighted average of 25 ppm, or 110 ppm nitrate equivalent. Sewage treatment plants and wineries use percolation ponds for waste disposal and are other potential nitrate sources.

The Clovis Sewage Treatment Plant has provided primary treatment for essentially domestic sewerage from the municipality of Clovis since 1955. Disposal of sewage effluent is by percolation on about 30 acres west of Tarpey Village. Total nitrogen content of the effluent was 28.0 ppm, or 123 ppm nitrate equivalent, in 1968. About 70 ppm nitrate were sampled in the effluent in 1963 and were apparently related to operation of the trickling filters. Nitrate in the past several years has averaged 10 to 20 ppm. The average effluent flow is about 1.0 million gallons per day and in recent years 2 wells near the plant have monitored the highest nitrate contents reported in the F.C.M.A. for pumping wells. Water from these wells has exceeded 120 ppm nitrate. Domestic wastes from the eastern part of Tarpey Village are treated by Fresno County Sanitation District No. 1, which was formed in 1955. The average effluent flow is about 0.2 million gallons per day from an activated sludge unit. The total nitrogen content in 1963 was 29.0 ppm, or 128 ppm nitrate equivalent. The pond effluent is percolated from 5 acres of ponds southeast of the Italian Swiss Colony Winery.

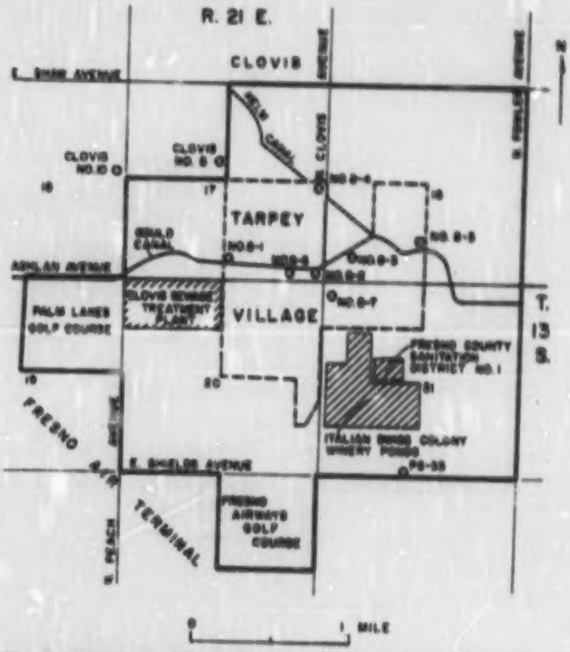

Fig. 6. Tarpey Village Area and wells of interest (circles)—waste dischargers are cross-hatched.

The Italian Swiss Colony Winery, or Allied Winery, had a wastewater flow of 40 million gallons in 1968. Disposal of wastewater is by land flooding of about 110 acres south and east of the winery, and disposal of clear water into the Gould Canal. Wastewater analyses by the California Department of Water Resources (1965) indicated potassium content was 920 ppm, sulfate content was 177 ppm, sodium content was 102 ppm, and chloride content was 41 ppm. However, no determinations were reported for total nitrogen during the winery season. The author took 2 samples of wastewater from ponds of the Italian Swiss Colony Winery in November, 1970. Total nitrogen content for one sample was 100 ppm, whereas that for a second sample was 250 ppm. These values have nitrate equivalents of 440 and 1,100 ppm, respectively. Winery wastewater seems to have a total nitrogen content similar to that for meat-packing plants. Winery wastewaters are a potential source of nitrate in ground water that have been neglected in past studies in the F.C.M.A.

Static water levels declined in the Tarpey Village Area from the 1950's to 1962 or 1963. This trend was reversed and rising water levels have occurred from 1963 to the present. Depth to water in 1969 ranged from less than 30 feet in the eastern portion to more than 70 feet in the western portion. The predominant direction of ground-water flow beneath the Tarpey Village Area is southwest, and the hydraulic gradient averages 25 to 30 feet per mile. This area is in a transition zone between the cobble and sand zones of the northern F.C.M.A.

and the abundant clays to the south. Cobbles are generally absent and a soil with no hardpan occurs throughout much of the area. Transmissibility is rather uniform and averages 180,000 gpd/ft.

Nitrate hydrographs show long-term increases for most wells. However, wells perforated in deeper parts of the aquifer had a constancy of nitrate. Historical records indicate a substantial increase in nitrate content occurred between 1958 and 1963. The septic tank part of Tarpey Village was developed, the Clovis Sewage Treatment Plant was reactivated, and the Fresno County Sanitation District No. 1 treatment plant was built during or shortly prior to this period. Five wells with chloride and nitrate hydrographs had a similarity of nitrate and chloride short-term trends, as in the Figarden-Bullard Area. However, 5 other well hydrographs had nitrate short-term trends opposite to those of chloride. The latter group of wells were at or near the Clovis Sewage Treatment Plant and were apparently affected by sewage effluent.

Analyses of samples of wastewaters and ground water were plotted on a trilinear diagram. Typical ground water in septic tank areas contains less than 10 percent sulfate and less than 10 percent chloride on a reacting value basis. Ground water near the Clovis Sewage Treatment Plant has sulfate ranging from 10 to 20 percent and chloride from 10 to 20 percent. Fresno County Sanitation District No. 1 and Clovis Sewage Treatment Plant effluent have similar compositions to the latter ground-water samples. Italian Swiss Colony Winery effluent has about 10 percent chloride and 30 percent sulfate. A trilinear diagram for ground water in the Tarpey Village Area showed that septic tank effluent, the Clovis Sewage Treatment Plant, and the Italian Swiss Colony Winery were the primary sources of nitrate. Some wells had one primary source, whereas other wells apparently had more than one nitrate source.

Seasonal nitrate analyses for District 8 wells in 1967, 1969, and 1970 showed substantial decreases as the summer progressed. Virtually all of these wells are on canal banks or nearby, and with the limited hardpan development of the area, abundant recharge from canals is a certainty. An analysis of aquifer penetration revealed a nitrate stratification as in the Figarden-Bullard Area. However, equivalent nitrate concentrations were about 40 feet deeper in the aquifer beneath the Tarpey Village Area. The primary reason for higher nitrate contents at greater depths is the presence of nitrate sources other than septic tanks. Ground water moving from beneath these sources to wells in the area follows flow paths that take nitrate deeper into the aquifer.

On the basis of available data, wells at the Clovis Sewage Treatment Plant, Clovis No. 8 and No. 10, Well No. 8-1, and wells at the Palm Lakes Golf Course have been primarily affected by sewage effluent. Four of the 6 wells with nitrate over 45 ppm at least once in the Tarpey Village Area were near the Clovis Sewage Treatment Plant. Wells No. 8-2, 8-6, and 8-4 have been primarily affected by septic tank effluent. Wells No. 8-3 and 8-7 and a well at the Italian Swiss Colony Winery have been primarily affected by winery wastewaters. Nonurban land immediately upgradient of Tarpey Village is idle and underlain by ground water with nitrate contents less than 15 ppm. There is a small agricultural contribution to ground-water nitrate in this area, because of the lack of nitrogen fertilization for several decades. Nitrate from agricultural areas further east is diluted by ground-water inflow before reaching the Tarpey Village Area. The septic tank part of the Tarpey Village Area and the Italian Swiss Colony Winery are planned to be connected to the Fresno sewerage system within the next several years. After these connections, nitrate content will decrease in most ground water of the area, but the Clovis Sewage Treatment Plant probably will continue to be an important nitrate source.

MAYFAIR-FRESNO AIR TERMINAL AREA

The Mayfair-Fresno Air Terminal Area (Figure 7) has a high septic tank density and previous studies have related high nitrate contents in ground water to septic tank effluent. However, a number of potential sources are upgradient of this area. The

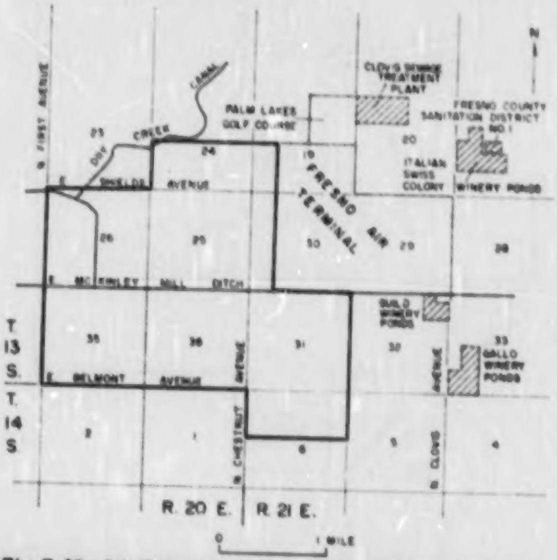

Fig. 7. Mayfair-Fresno Air Terminal Area—waste dischargers are cross-hatched.

Clovis Sewage Treatment Plant, Italian Swiss Colony Winery, and Fresno County Sanitation District No. 1 treatment plant were previously discussed. Anhydrous ammonia is widely used on agricultural lands immediately east of the Fresno Air Terminal and ground water in this area had a nitrate content ranging from 15 to 25 ppm in 1970. About 500 to 600 acres were also irrigated in or near the Fresno Air Terminal in 1970. Nineteen wells have had nitrate contents over 25 ppm and 6 of these wells have had nitrate over 45 ppm at least once in the Mayfair-Fresno Air Terminal Area.

The Guild Winery or Alta Vineyards Winery had a wastewater flow of 16 million gallons in 1968. About four million gallons were disposed of in Mill Ditch and through dry wells. This wastewater had the lowest waste strength of samples from the 3 wineries on Clovis Avenue sampled by the California Department of Water Resources (1965). Sampling of wells at the winery and within one-half mile downgradient of the disposal ponds indicated low nitrate contents in 1970. Although part of this was due to the existence of moderately deep wells, apparently the relatively small volume of percolated wastewater minimized the contribution to ground-water nitrate.

The Gallo Winery had a wastewater flow of 50 million gallons in 1968. Disposal of all wastewater prior to 1970 was by land flooding of about 260 acres south and east of the winery. This winery has the highest wastewater flow of the 3 wineries on Clovis Avenue; all of the water was formerly percolated; and the waste has the greatest strength of all 3 wineries. A sample of pond water was taken by the author in June, 1970 prior to connection of Gallo Winery to the Fresno sewerage system. Total nitrogen was 410 ppm, or about 1,800 ppm nitrate equivalent. Two of 3 wells sampled near the disposal ponds had nitrate over 45 ppm.

Ground-water flow is primarily southwest in the northern portion and west in the southern portion. Depth to water in 1969 ranged from 60 feet in the southeastern part to 90 feet in the northwest. Water levels declined from 1958 to 1965 at about 4 feet per year, but have risen 1 to 3 feet per year thereafter. Lithologic sections demonstrate that this area is in a transition zone from the sands and cobbles of the northern F.C.M.A. to clays of the south. The area is generally free of cobbles in the subsurface except for a lens in the central portion. A shallow, thick clay occurs from 10 or 20 to about 60 feet beneath much of the area.

Soils of the Mayfair-Fresno Air Terminal Area are of the Madera Series. Most of the soil north of East McKinley Avenue is Madera sand, which has no hardpan. Hardpan in the remainder of the area lacks the impermeable nature of that in the older San Joaquin soils to the north and east. Transmissibility of most of the aquifer is about 180,000 gpd/ft. However, a lens-shaped area in the vicinity of East McKinley Avenue has a transmissibility of 370,000 gpd/ft.

Historic nitrate analyses show that all wells sampled in 1951 had concentrations less than 15 ppm. Nitrate contents had greatly increased by 1963. The number of wells with nitrate content over 25 ppm remained relatively constant from 1963 to 1969. Eighteen hydrographs had long-term increases in nitrate. Most of these hydrographs were for wells with a cased depth of less than 150 feet. Six hydrographs had nitrate decreases, but most of these records were for short periods. Wells with decreasing nitrate trends were probably affected by canal recharge during the wet years of 1967 and 1969. Fifteen hydrographs had constant nitrate trends and most of these were for wells cased to at least 150 feet depth. Fifteen well hydrographs had nitrate short-term trends similar to those of chloride. These well hydrographs have the dominant trend of the Figarden-Bullard Area, a trend related to septic tank effluent. Only 3 wells' hydrographs had opposite nitrate and chloride short-term trends, and these wells were downgradient from the Clovis Sewage Treatment Plant.

Seasonal nitrate analyses for 1967, 1969, and 1970 indicate consistent decreasing contents during the summer, as in the Tarpey Village Area. This feature is also due to canal recharge. An analysis of aquifer penetration revealed a step-like pattern of nitrate as in the Figarden-Bullard and Tarpey Village Areas. However, few shallow wells in the Mayfair-Fresno Air Terminal Area have low nitrate contents. Thus, there is some indication of a "nitrate cap" as described by Stout, Burau, and Allardice (1965) in San Luis Obispo County, California. Several wells in the area have nitrate contents too high to fit the step-like pattern. Two of these wells are downgradient of the Clovis Sewage Treatment Plant and 2 others are downgradient of the Gallo Winery.

A trilinear diagram was prepared for samples of wastewater and ground water in the Mayfair-Fresno Air Terminal Area. The anion portion was most useful and suggests that septic tanks have contributed the majority of nitrate to the ground water. This diagram and chloride concentrations indicate downgradient movement of sewage effluent for at least 1 or 2 miles from the Clovis Sewage Treatment Plant. Similar data indicate downgradient movement of winery wastewater from the Gallo Winery ponds for at least 1 or 2 miles. Ground-water velocities are estimated to range from several hundred to 1,000 feet per year in this area. The downgradient effect of recharged wastewater is limited by dilution and dispersion in the aquifer.

Most wells with high nitrate contents are in the southern part of the area, and no wells with high nitrate are in the central part. Hardpan exists in some parts of the northern portion and may limit the percolation of high nitrate waters. Cobble zones disperse and dilute the high nitrate recharge waters in the central portion. Ground water in the Mayfair-Fresno Air Terminal Area with nitrate over 25 ppm in 1969 covered an area larger than any other part of the F.C.M.A., except near the Fresno Sewage Treatment Plant. This situation is related to the high density of septic tanks and the presence of other nitrate sources. The absence of cobble zones and impermeable hardpan favor higher nitrate contents in ground water. The lower transmissibility, as compared to the northern part of the F.C.M.A., also lessens the dilution of high-nitrate recharge waters. Nearby upgradient agricultural lands contribute some nitrate to the urban area. The Mayfair-Fresno Air Terminal Area septic tank portions began conversion to the Fresno sewerage system in 1970, and the Guild and Gallo Wineries were also connected in summer, 1970. The future nitrate situation will greatly improve in this area with these connections, but the Clovis Sewage Treatment Plant will probably continue to be an important nitrate source to the northeastern portion.

DOWNTOWN FRESNO AREA

The Downtown Fresno Area (Figure 8) has been sewered since 1891 and no sewage treatment plants are within several miles of the area. Settlement occurred in the late nineteenth century, and most of the early industrial development occurred here. Upon careful examination, a number of potential nitrate sources can be found in or near the Downtown Fresno Area. Urban parts of the city surrounding the area used septic tanks many years ago. The townsite of Calwa, which covers about 500 acres, presently is unsewered and is one-half mile southeast of the area. The Mayfair-Fresno Air Terminal Area is also unsewered and extends to within one-half mile of the Downtown Fresno Area. Ten wells have had nitrate over 25 ppm at least once and 2 of these wells have had nitrate over 45 ppm. Industry and agriculture also comprise potential sources of nitrate to the area.

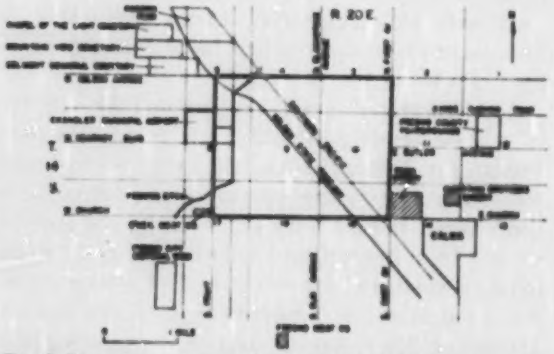

Fig. 8. Downtown Fresno Area—present and former waste dischargers are cross-hatched.

Meat-packing plants have high nitrogen wastes. The concentration of organic plus ammonia-nitrogen in such waters is quite high, ranging from 100 to 300 ppm, or 440 to 1,320 ppm nitrate equivalent (American Water Works Association, 1967). Two meat-packing plants are within 1.5 miles and southwest of the area. Historically, a number of industries used independent waste disposal facilities prior to connection to municipal sewerage systems. Roma Winery has a wastewater flow of 1.0 million gallons per day and is at the southeastern corner of the Downtown Fresno Area. This winery was unconnected until 1936. Mont LaSalle Vineyards or Christian Brothers Winery is one mile east of the Roma Winery and was unconnected prior to 1953. Both wineries may have contributed substantial amounts of nitrate before connection to municipal sewerage systems. Several chemical industries used independent waste disposal facilities in 1969, but wastewater flows were too small to affect wells thousands of feet distant.

Many cooling water return wells are in or near the Downtown Fresno Area. A previous study stated that water quality was unaffected by the cooling process (California Division of Water Resources, 1952). However, the highest nitrate contents in the F.C.M.A. in 1951 were sampled near 2 recharge wells. High nitrate ground water also was found near the Fresno County Hospital cooling return well in 1970. Apparently, either recharge water is enriched with nitrate derived from the refrigerant, or other sources of nitrate have been injected in some of these wells. The Fresno Sewage Treatment Plant is about 3 miles southwest of the Downtown Fresno Area. The California Department of Water Resources (1965) assumed that sewage effluent from this plant had not reached the Downtown Fresno Area by 1963. Most historical water level contour maps have shown a slight gradient towards the treatment plant from downtown Fresno. However, these maps have been based on only a few wells, and were usually drawn for December conditions. Ground-water elevation contours for the fall of some years, such as 1951, show either a flat water table or a gradient toward the Downtown Fresno Area. Northeasterly movement of ground water from the Fresno Sewage Treatment Plant toward the urban depression cone was possible during summer pumping conditions.

Agricultural areas southwest of the Downtown Fresno Area may contribute nitrate to ground water, as anhydrous ammonia is in wide use. Large dairies are additional sources of nitrate in this vicinity. The Fresno County Disposal Yard is within 1 mile of the Downtown Fresno Area, and solid waste disposal sites are potential nitrate sources. Several old cemeteries lie northwest of the area and may have contributed nitrate decades ago when waterlogging occurred over much of the F.C.M.A.

The extreme southern portion of the urban cone of depression in the F.C.M.A. is beneath the Downtown Fresno Area. Ground water can potentially enter the area from almost any direction. Depth to water in 1969 ranged from 50 feet in the southwest to 83 feet in the northeast. No major canals traverse the area except for Dry Creek Canal at the northwest corner. Water levels declined until 1966, and have stabilized up to the present. The Downtown Fresno Area has abundant clays in the subsurface, especially below several hundred feet depth. A thick clay occurs over much of the area at a depth interval of 10 or 15 to about 75 feet. Soils are of the Madera Series, and Madera sand occurs throughout much of the area. Transmissibility is highly variable and ranges from 60,000 gpd/ft in the northwest to 370,000 gpd/ft in the northeast.

Almost all wells in the F.C.M.A. with nitrate contents over 15 ppm in 1951 were in or near the Downtown Fresno Area. This was prior to extensive development of suburban areas on septic tanks and nitrogen fertilization on agricultural areas. Wells with nitrate over 25 ppm in 1958 were in an elongate areal distribution, which trended northeast-southwest. Significant amounts of chloride are present in ground water of the Downtown Fresno Area. This is in contrast to the Figarden-Bullard, Tarpey Village, and Mayfair-Fresno Air Terminal Areas.

Most wells with long-term nitrate hydrographs have either decreasing or constant trends. Short-term chloride and nitrate trends were similar for 5 well hydrographs, but opposite for 5 others. Seasonal nitrate analyses for 1969 and 1970 showed both increasing and decreasing contents as the summer progressed. An analysis of aquifer penetration showed no stratification of nitrate as in septic tank areas of the F.C.M.A. However, there was a lack of data for aquifer penetrations of less than 80 feet. Many wells with aquifer penetrations ranging from less than 60 to more than 160 feet had nitrate contents between 15 and 25 ppm. This distribution suggests that nitrate did not originate from a surface source in the immediate vicinity of the Downtown Fresno Area. A trilinear diagram for ground water in the area demonstrated at identical composition to ground water at the Fresno Sewage Treatment Plant.

Several wells with nitrate content over 15 ppm are within one-half mile of cooling return wells. Two wells with nitrate content over 15 ppm are near a meat-packing plant. One well with nitrate content over 15 ppm is located between the Roma Winery and Mont LaSalle Vineyards Winery. Two wells with nitrate content over 15 ppm are near septic tank areas. However, there are at least 5 wells with nitrate over 15 ppm for which a source is not immediately apparent. Several facets of the nitrate distribution in ground water of the Downtown Fresno Area should be explained. Key factors are the relatively high nitrate contents of the 1950's, the high chloride content, the decreasing long-term nitrate trends, the abundance of opposite nitrate and chloride short-term trends, the presence of nitrate in concentrations above the background level at considerable depth in the aquifer, and the trilinear plot for ground water.

Water samples were collected from many wells in July and August, 1970, in the area between downtown Fresno and the Fresno Sewage Treatment Plant. Chloride was analyzed by the Mohr titration method utilizing a Hach field testing kit. Zones of chloride content greater than 25 ppm were delineated (Figure 9). The largest zone extended from the Fresno Sewage Treatment Plant northeast to the Downtown Fresno Area. Smaller zones were near the Clovis Sewage Treatment Plant, the Gallo Winery, and the Fresno County Hospital. Chloride content was also greater than 45 ppm in the smaller zones. The highest chloride contents in F.C.M.A. ground water in 1970 were monitored at the Fresno Sewage Treatment Plant.

Historical records in Fresno state that waterlogging occurred at the treatment plant site in the early 1900's. This problem was solved by ground-water pumpage at the plant site and in the nearby urban area in the 1920's. It is significant that the original treatment plant site was one mile east of the present plant, and thus one mile closer to the Downtown Fresno Area. Sewage effluent from the Fresno Sewage Treatment Plant has played an important part in recharge to ground water of the F.C.M.A. since 1891. The northeasterly movement of ground water beneath the treatment plant was initiated with the greatly increased pumpage in the urban area between 1910 and 1920. Some wells in

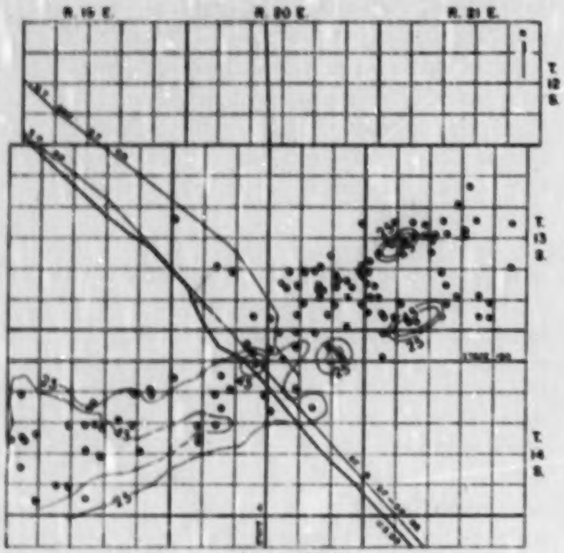

Fig. 9. Distribution of chloride in ground water in 1970—contours are in parts per million and circles are locations of sampled wells.

the Downtown Fresno Area were monitoring fairly high chloride contents by 1930. Historical chloride analyses from that time to the present show an elongate pattern of wells with high chloride contents. The northeast-southwest trend of the high chloride zone in the Downtown Fresno Area implies a source to the northeast or southwest. However, as no high chloride source of large volume occurs to the northeast, the source must lie to the southwest.

The relatively high nitrate contents of the 1950's were related to ground-water inflow for several decades from the vicinity of the Fresno Sewage Treatment Plant. This inflow was accentuated by urban water level declines. However, by 1965 water levels had stabilized in the Downtown Fresno Area and inflow from the southwest diminished. Thus, decreasing trends have occurred for many nitrate hydrographs, especially over the past decade. The high chloride contents of the Downtown Fresno Area are a direct reflection of sewage effluent, as chloride is nearly an ideal tracer in this environment. The abundance of opposite nitrate and chloride short-term trends and the trilinear plot of ground water confirm that the Fresno Sewage Treatment Plant has been the primary source of nitrate. Nitrate at considerable depths in the aquifer was caused by movement of nitrate from a source several miles distant. Flownet considerations demonstrate that sewage effluent from the mound beneath the plant would tend to move into deeper portions of the aquifer.

Septic tank effluent from the Mayfair-Fresno Air Terminal Area has reached the northeastern portion of the Downtown Fresno Area and has been the dominant nitrate source since about 1963. Septic tanks at Calwa have contributed some nitrate to the southeastern part of the area. Winery wastewaters have likely contributed nitrate to ground water in the southeastern portion of the area. Meat-packing plants have contributed nitrate near the southwestern portion. However, the dominant source has been the Fresno Sewage Treatment Plant.

With the planned conversion of septic tank areas and industries on independent waste disposal units to municipal sewerage systems, it is inevitable that nitrate conditions will greatly improve within a period of years in most of the F.C.M.A. However, in the vicinity of the urban depression cone, nitrate contents will likely increase. This is due to the planned concentration of almost all of the total nitrogen load of the urban area at one site. Unless nitrate removal is practiced, high nitrate water from beneath the Fresno Sewage Treatment Plant will move toward the Downtown Fresno Area. Increased urban pumpage and greater sewage flows will favor movement away from the mound beneath the plant.

SUMMARY

Studies in septic tank areas indicate substantial nitrate concentrations in ground water beneath some parts and small nitrate concentrations below others. These differences are related to septic tank density, soil characteristics, length of septic tank development, and hydrogeologic factors. Concentrations of nitrate less than 25 ppm are usually found in areas that have extensive cobble zones in the subsurface. There is an inverse relation between aquifer transmissibility and nitrate content. The relation of nitrate content to cobble zones and transmissibility is due to dispersion and dilution of high nitrate recharge from septic tank disposal systems. Areas underlain by impermeable hardpan have low nitrate contents, indicating a lack of percolation of high nitrate water.

Ground-water nitrate contents at the Fresno Sewage Plant depend on pond operation, temperatures, and total nitrogen contents of sewage effluent. When ponds are not periodically dried out, anaerobic conditions prevail and nitrate contents in ground water near the water table are less than 5 ppm. However, when ponds are periodically dried out, aerobic conditions develop and at the beginning of flooding cycles, nitrate content near the water table can locally exceed several hundred ppm. High chloride contents trace the extent of sewage effluent in the aquifer and water samples from wells plot in a characteristic part of the trilinear diagram. Short-term trends for chloride and nitrate hydrographs are commonly opposite near sewage treatment plants in the F.C.M.A.

The highest nitrate contents occur in the upper 50 or 60 feet of the aquifer beneath septic tank areas. Nitrate stratification is obscured when other sources are present, due to the derivation of nitrate from nearby areas by ground-water inflow. Trilinear diagrams for constituents in ground water and short-term nitrate and chloride trends in septic tank areas differ from those for ground water affected by sewage effluent.

An analysis of two high nitrate areas near the Fresno Air Terminal indicates septic tanks contributed most of the ground-water nitrate. However, wineries and the Clovis Sewage Treatment Plant are significant local sources. Winery wastewaters were sampled and had a total nitrogen content ranging from 4 to 10 times that found in typical domestic sewage. Wineries have been important sources of ground-water nitrate, as they have existed since the early 1900's. The agricultural contribution of nitrates to ground water in the urban area is small due to dilution as downgradient movement occurs.

Ground water beneath the Downtown Fresno Area is in a significant hydraulic depression cone. Extensive northeasterly flow of ground water from the mound beneath the Fresno Sewage Treatment Plant took place for many decades. Moderate concentrations of nitrate occur at depth in the aquifer and are related to the inflow of sewage effluent from a source several miles distant. Although other sources have contributed nitrate to the ground water, sewage effluent is the dominant source as indicated by chemical and hydrologic data.

Twenty-six wells in the F.C.M.A. have sampled nitrate over 45 ppm at least once since 1947. Seven of these wells have been near the Fresno Sewage Treatment Plant. Six wells west and southwest of the Fresno Air Terminal have sampled nitrate greater than 45 ppm at least once. Five wells in the vicinity of the Clovis Sewage Treatment Plant had nitrate exceeding 45 ppm at least once. Other ground water with nitrate greater than 45 ppm in the F.C.M.A. was in the Downtown Fresno Area, in septic tank portions of Figarden-Bullard Area, in the agricultural areas north and east of Fresno, and near the Gallo Winery.

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DISCUSSION

The following questions were answered by Kenneth D. Schmidt after delivering his talk entitled "Nitrate in Ground Water of the Fresno-Clovis Metropolitan Area, California."

Q. *Can you describe the hardpan geologically?*
A. This hardpan has been described by M. G. Croft and R. J. Janda of the U. S. Geological Survey as part of a study of the alluvial formations of the eastern San Joaquin Valley. It is in the oldest soil of the area, is cemented by iron salts, and belongs to the noncalcic brown soils that occur in the eastern part of the San Joaquin Valley. The hardpan is composed of firmly cemented soil particles, and is dense and impervious. It has a low humus content and contains no alkali.

Q. *How did the nitrate (NO$_3^-$), ammonium, and organic nitrogen vary with the nitrate distributions?*
A. These are important parameters to consider in the ground water besides nitrate. There is less than 0.1 ppm ammonium or nitrate in the aquifer under-

neath the septic tank areas. At the Fresno Sewage Treatment Plant there are some ammonia contents between 0.5 and 1 ppm. There is an inverse relation between ammonia content and nitrate content on a seasonal basis. Some wells have shown as much as 5 ppm ammonia, which is an indication that the ability of these soils to continue retaining the ammonia form has perhaps been reached. Nitrite contents have generally been less than the limits of detection in all ground water of this area, as sampled by pumping wells. Organic nitrogen has not been tested for to a large extent, but contents are below the limits of detection.

Q. *Did you determine any oxidation potentials?*
A. No, I didn't, and perhaps this would be a very important thing to do. There are several areas where investigators have actually worked with this, such as Stewart and others in Colorado. Apparently, there is good correlation between oxidation potential and nitrate above the water table in some areas and a poor correlation in other areas. Obviously, studies in the unsaturated zone would be necessary to completely understand nitrate in ground water of the Fresno area. Oxidation potential would be an important parameter; however, my analysis was confined primarily to water in the aquifer.

Q. *Has there been any plan to line evaporation ponds at the Fresno Treatment Plant? Are many of these ponds already lined?*
A. No ponds are lined at present. About 80 to 85 percent of the effluent disposal at the Fresno City Sewage Plant is by percolation. If the ponds are lined, then a much larger waste disposal problem will occur. Approximately 1440 acres of percolation ponds are necessary at present and on the average of 10 percent of the effluent is used for irrigation on nearby farms. There is some evaporation also, which makes up the remainder. I think the best solution will not be to line the ponds but to continue percolation of the water. The solution involves the nitrogen compounds themselves, because recent literature suggests that with refined technology we are learning how to control the total nitrogen content of effluent. The City of Tucson Sewage Treatment Plant has been able to substantially decrease total nitrogen contents of the effluent in recent years.

Q. *Ken, you mentioned the use of agricultural fertilizers. Are super-phosphates used in this area? Also, what fluoride levels were found in the ground water?*
A. About 90 to 95 percent of the agricultural fertilizer used in this area is anhydrous ammonia. Farmers use virtually no significant amounts of super-phosphates to my knowledge. Fluoride levels are below 0.1 ppm in this whole area except in two septic tank areas where they use fluoridation units. Fluoride levels ranging from about 0.1 to almost 1 ppm have shown up in the ground water within 3 to 5 years since installation of these fluoridation units.

Q. *Here's another one on agricultural sources and nitrates. To what extent have agricultural sources of nitrates been examined in the San Joaquin Valley?*
A. Many studies along this line have been done. If one looks at the nitrogen literature not only in the San Joaquin Valley but elsewhere in the country, one may conclude that prejudice has been evident among some investigators. In the Fresno area, agricultural workers have neglected the wineries, and have generally not considered the effect of fertilizers on ground water near urban areas. One common argument is that plants use all of the nitrogen in the fertilizer. I think we have to recognize that the true position is somewhere between no effect and a substantial effect. That is, most farmers don't want to apply fertilizer that would be leached in great amounts. A farmer is going to try to be efficient, but he usually is not going to be 100 percent efficient and recover all of the nitrogen added. Agriculture contributes to nitrate in irrigated areas near my urban study area. The nitrate contents beneath agricultural areas varied with the transmissibility and other factors, and ranged from 15 to 25 ppm where the transmissibility was lowest. So in the Fresno area, agriculture near the urban area is not really causing nitrates that are over 45 ppm.

One of the important problems now in California is how to get rid of the nitrate that is going to be in the California master drain when it is built. They have done experiments at Firebaugh, which is northwest of Fresno, and have been quite successful in denitrification. About 25 ppm nitrate is the average nitrate content in irrigation return water in the San Joaquin Valley. Now, in some areas nitrates occur in amounts over the limit and it is due to agriculture. Many factors must be considered, such as fertilizer practice, irrigation, aquifer characteristics, and well construction.

Q. *I have 2 questions here I think are similar to what you're discussing. Has spray irrigation been considered to recycle the nitrate back to the agricultural area? Aren't these high nitrate waters worth something as an irrigation water source?*
A. This is something that people working near Phoenix, Arizona have considered. Herman Bouwer

presented a paper on this at the Arizona Academy of Science meeting in April. It seems logical to consider using sewage effluent for its nutrient value. One major problem is that in the future we are going to, in places such as Arizona and California, grow more and more high yield crops. A high nitrogen load all the time is not desirable on these crops because of rank growth of the vegetation. However, effluent may be used on field crops such as safflower or may be diluted and used on many crops.

The idea in Phoenix is to have sewage plants along a dry stream bed, with a number of percolation basins. Water will be recharged and later pumped by wells after moving a sufficient distance through the soil. They believe that by operating the ponds in a certain manner, such as controlling the aerobic vs. anaerobic conditions, one can get almost any nitrate content desired in the recharged effluent. Hopefully, they will be able to deliver the nitrate load that the farmer wants when he wants it. One can imagine that with different crops growing and a number of different farmers, this is a formidable task. The concept of utilizing the nutrient value of nitrate in well water or sewage effluent is worthwhile and will eventually be perfected.

Q. *In your discussion, one person wants to know how did you eliminate lawn fertilizers as a nitrate source in the suburban septic tank areas? Was there no early fertilizer usage in the Fresno area?*
A. Let me answer the second part of that question first. The important point about fertilizers is the drastic change that occurred between 1950 and 1970, when nitrogen fertilizer use increased by 600 percent. Fertilizer use in this area was small prior to 1950. As regards lawn fertilizers in the septic tank areas, that's a very good question. In the septic tank areas where there is hardpan, nitrogen compounds will not percolate and generally will not enter the ground water. In other areas where the impermeable hardpan is absent, nitrates could build up in the ground water. I did not scientifically eliminate lawn fertilizers as a source, but I think a simple calculation, if we knew the amounts used, would show only small accretions to the groundwater nitrate.

Q. *Shouldn't the inverse relationship you noted be between nitrate content and the specific groundwater discharge rather than the transmissibility alone?*
A. This is a point that is theoretically sound. My concept is that we are adding nitrate at the land surface, and that it will be diluted in relationship to the transmissibility of the aquifer. Of course, water flows through the aquifer based not only on transmissibility, but on the hydraulic gradient and width of flow. However, the gradient tends to be uniform in each one of the small areas studied. Thus nitrate content on a local scale does depend primarily on the transmissibility, as the gradient is rather uniform.

Q. *What percent of irrigation water applied to fields is returned to ground water by infiltration? What percent is this of the total recharge?*
A. Let's consider eastern Fresno County and the agricultural areas in it. The best estimates, which are fairly reliable, indicate that farmers are applying about 4 to 5 acre-feet per acre per year. The consumptive use of the crops growing there is about 2.5 acre-feet per acre per year. The percent of applied water that returns to the ground water is thus about 30 to 40 percent.

Q. *Let me finish the other part of the last question—what percent is this of the total recharge?*
A. I don't have the vaguest idea. We don't really have valid estimates of the canal recharge and other components of the water budget. Return flow comprises one of the major unknowns in many water budget studies in semiarid and arid environments.

Q. *How about naturally occurring nitrate as in some of the salt pans in the inner mountain basins, such as Owens Valley, Death Valley, etc.?*
A. J. H. Feth, in 1966, summarized data on nitrogen compounds in water. He points out that natural sources of nitrate are associated with caves, playa deposits and caliche. None of these occur in or near Fresno's urban area.

Q. *Do you think that your sampling frequency is sufficient to really establish confidence in water quality trends?*
A. The frequency you're probably referring to is as shown on the water quality hydrographs. I more or less financed this study myself; for this and other reasons, I wanted to take an area where the data was available and see what could be done. Now it's probably easier to go out with a large sum of money, take a large number of water samples, and have good data to interpret. However, as a practical problem, we should sometimes force ourselves to use available data. I think the trends are meaningful. I looked at all available analyses for specific wells and used judgment to cast out erroneous or atypical values. There are many problems, such as laboratory errors, pumping time, contamination, and time between sampling and analysis. Of course, different methods have been used at different times. Some of these problems cannot be solved

because these are the only historical data available. Because these trends could be related to actual waste disposal operation at the land surface and hydrogeologic factors, I would argue that they are meaningful. However, they are by no means the ultimate—and more detailed sampling is necessary for precise interpretation.

Q. *This might be along the same line, Ken. It says here the almost perfect positive correlation of nitrate and chloride in septic tank areas and the almost perfect negative correlation for sewage plant effluent hardly appear to be just chance occurrences. Can you speculate about any casual mechanisms?*

A. The similarity of chloride and nitrate behavior in water, of course, is well documented in the literature and would be expected from geochemical and other considerations. Chloride and nitrate are both soluble and mobile in most ground-water systems. There is a correlation between the chloride and nitrate in septic tank areas because chloride and nitrogen compounds are in the effluent, and these ions have similar geochemical characteristics in the aquifer; they are both soluble and they are not adsorbed or exchanged.

The opposite trends are more difficult to explain. An explanation may be somewhat theoretical, but it is interesting. There was evidence of denitrification between the Fresno Sewage Treatment Plant. I believe that many workers have overemphasized denitrification and have used it when the other items didn't balance out. I believe that if one considers chloride or some other ion that does not undergo denitrification or nitrification, valuable conclusions can be drawn. Chlorides in the ground water for quite a distance around the sewage treatment plant are generally the same as in the effluent. This indicates that there is little dilution of recharged effluent near the plant. This is true because the quantity of effluent is so large, about 25,000 acre-feet per year. However, nitrates are not correspondingly high in the same area, although some high contents do occur. Denitrification completely eliminates nitrogen compounds, as they go off as gaseous forms and are no longer in the water. Nitrate would tend to be lower, generally due to the anaerobic conditions developing in the area, and denitrification.

Another alternate could be related to a concept discussed last year in the *Journal AWWA*. Malhotra and Zanoni discussed the interference effect of high chloride ion contents on nitrate determination. High chloride contents near sewage plants could cause interference with the phenoldisulfonic method for nitrate determination. Thus with higher chlorides, nitrates may be erroneously low in some cases.

Q. *Were bacterial analyses made on water so obviously contaminated by primary waste effluent from the Fresno Treatment Plant?*

A. Bacteriological sampling is something I did not get involved with to a great extent. There are only 1 or 2 wells in the urban area that have shown biological contamination. This is largely, in my opinion, due to the regulations that are imposed by the county for septic tank construction, that the wells are generally deep, and are not usually open in the upper 40, 50 or 60 feet of the aquifer. I am not familiar with biological sampling near the Fresno Sewage Treatment Plant.

Q. *Could a source of nitrate in downtown Fresno be leaking sewers? Could uniform vertical distribution be attributed to large vertical flow components associated with pumping, particularly in the central portion of the cone of depression?*

A. As for the first question, there were some areas not near sewage plants where chemical data pointed to sewage effluent as the source. A possible explanation would be related to leaking sewers. However, I made no positive correlation; in the future, it might be possible to do this.

In regard to the uniform vertical distribution—my reasoning is that effluent has moved from a mound beneath the Sewage Treatment Plant toward downtown Fresno. This water would spread out in a vertical sense, as one can visualize by flownet consideration. Hence, no stratification occurs as in the septic tank areas. The idea that the uniform distribution of nitrate is due to vertical flow is a good one, except for the lithology. The alluvium in that area contains a number of clay layers, much more than in any other part of the metropolitan area. Vertical flow would be greatly restricted, but still possible. There is a lot of pumping in the urban depression cone, and there may be a relation to distribution. But there is overwhelming evidence for the case I have presented. Historical nitrate and chloride data, water levels, trilinear diagram plots, and chemical hydrographs indicate movement of effluent from the Fresno Sewage Treatment Plant. Perhaps the most conclusive data are the high chloride contents between the plant and the downtown Fresno area.

The Use, Abuse and Recovery of a Glacial Aquifer[a]

by Edward M. Burt[b]

ABSTRACT

The inter-relationships between an industrial plant and a shallow sand aquifer of glacial origin are described. These relationships include industrial and potable water supplies, industrial and human waste water disposal systems, the hydraulics of the pollution of the ground-water aquifer and the types of corrective actions taken to re-establish the wise use of the ground-water resource. Also reviewed are the ground-water movement-quality relationship, well designs, method of drilling, well redevelopment and ground-water recharge.

INTRODUCTION

In the past few years, since the general public discovered the use, if not the literal definition, of the words "ecology" and "environment" many industries of this nation have received "black eyes." Some are deserved, but as in everything else, there needs to be a balance of perspective. A purpose of this paper is to illustrate the efforts of one manufacturer to maintain a peaceful coexistence with the environment. The efforts have spanned almost fifteen years–during which time scientists from public agencies and private concerns, administrators, engineers, architects and production personnel have worked together, agreed and disagreed, but have achieved the goal of preserving the environment.

Another purpose is to illustrate the inter-relationships among the ground disposal of wastes, the ground-water supply and well design, construction, and methods necessary to affect rehabilitation. While the specific information given is related to a single site, some of the conclusions drawn reflect experiences with other similar projects.

The firm involved is a manufacturer who produces chemical intermediates related to the pharmaceutical and agricultural industries. Some of the products are basic, while others are finished chemical products of highly complex composition. The corporation began on a small scale about fifteen years ago. The corporate capability and product diversification rapidly increased and in time the company merged with a major national corporation of international repute.

GEOHYDROLOGIC SETTING

The site is in Michigan and is situated within a surface watershed of approximately 12 square miles (see Figure 1). This shed is tributary to a larger watershed, shown as Creek "B," which eventually drains into one of the Great Lakes.

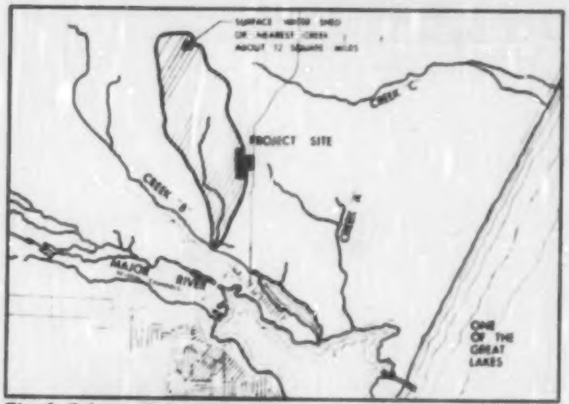

Fig. 1. Schematic location map.

The company chose the site because it offered access to a major population center, a large labor market, an abundance of ground water and reasonable isolation from intense development. The original facilities are shown in Figure 2. The major structures consisted of one building to house administrative offices, laboratory and maintenance facilities; another building for production; and a series of ponds for the ground disposal of cooling and waste waters.

The potable and industrial water-supply needs were originally met by a single well tapping the unconsolidated glacial sands. This tubular well was 6 inches in diameter and supplied approximately 50 gallons per minute. Water storage and pressure modulation was accomplished by a hydropneumatic tank.

A septic tank and tile field system adjacent to the administration building accommodated the sanitary wastes. Since both industrial and human wastes were disposed to the ground, shallow observation wells were installed between the administration building and the nearest residence. The responsible regulatory agency required the periodic sampling of the observation well waters for possible ground-water pollution.

The growth of the company led to a staged expansion program to develop the site as shown in

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

[b] Geologist, Williams & Works, 250 Michigan Street N.E., Grand Rapids, Michigan 49503.

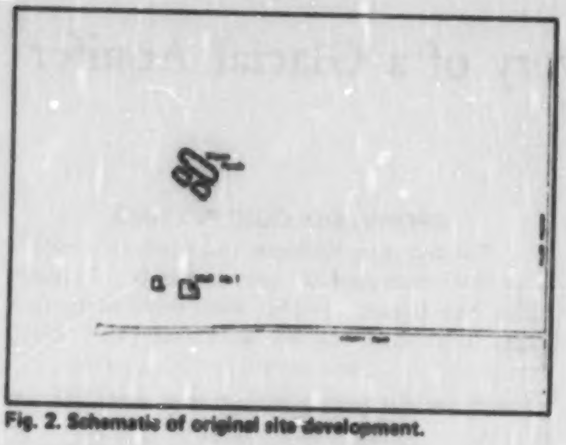


Fig. 2. Schematic of original site development.

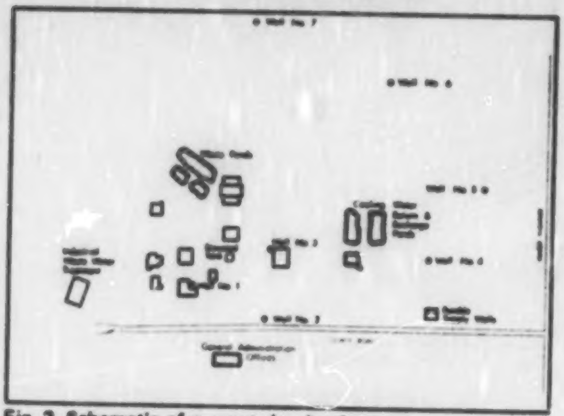


Fig. 3. Schematic of current site development.

Figure 3. However, during this expansion, pollution of the ground water was detected.

At that point in time, it was necessary that the company accomplish the following:

1. Develop a bacterially and chemically safe water supply for their personnel and the production processes.

2. Contain the pollution within the boundaries of their property.

3. Prevent additional pollution by developing suitable waste water treatment processes.

4. Restore the quality of damaged ground waters.

5. Maintain and expand the manufacturing capabilities of the firm.

In the past, the priority of these needs would assume a different order, depending upon the individual firm involved. In today's complex society and in light of modern science and technology, it is necessary that all be accomplished simultaneously.

The plant site lies within a large lake plain ancestral to the present Great Lakes. As such, the surface soils are sandy lake beds. The sand deposits range from 60-120 feet thick.

The surface watershed and the ground-water watershed are not hydrologically identical. Originally the ground watershed was larger than the surface watershed. The initial static water level of the water table was approximately 5 feet below the land surface.

Figure 4 indicates the original direction of ground-water flow within the unconsolidated glacial aquifer. The ground disposal of industrial waste water up the hydraulic gradient from the original well in conjunction with the company's use of water, modified the original direction of flow and resulted in the pollution of the water supply. The initial observation wells did not show the pollution of the aquifer because the waste water was intercepted by the well which furnished the company's total water supply.

The records of deep wells surrounding the site indicated the presence of another aquifer. This aquifer lies within the bedrock formation and is of limited thickness and areal extent. A few nearby domestic wells tapped this aquifer. Water samples from those wells indicated a higher mineral content than was found in the water from the sand aquifer.

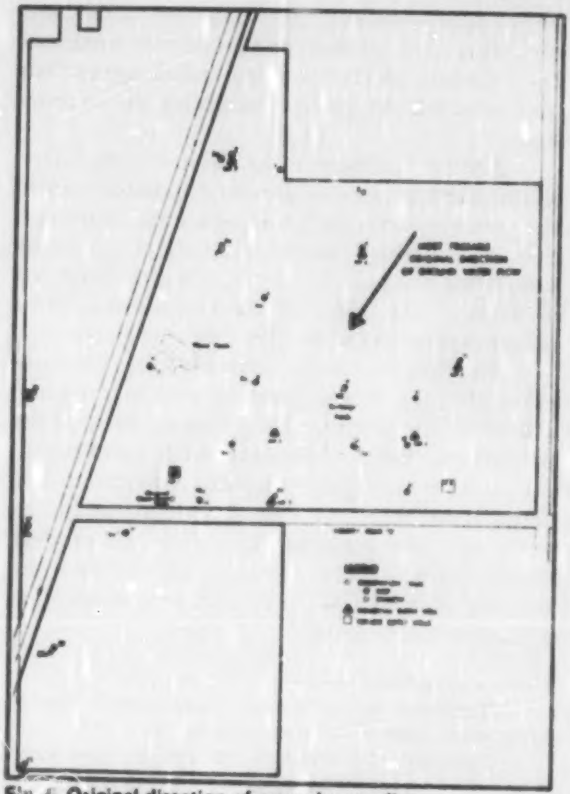


Fig. 4. Original direction of ground-water flow.

However, the degree of mineralization was within United States Public Health Service limits for potable drinking water purposes. The capability of the consolidated aquifer to supply water was explored and found to be significantly less than that of the unconsolidated aquifer.

The deeper bedrock formations include shales, limestones, dolomites and sandstones. Where saturated, these rocks contain saline water. Local deposits of petroleum and natural gas have been found in some of these sedimentary rocks. Beneath the sequence of sedimentary formations, igneous and/or metamorphic rocks occur. The basement rocks lie approximately one mile below the surface of the land.

From the standpoint of potable and industrial water supply, the upper 120 feet of the earth's mantle offer the only reasonable supply at this site.

The deeper bedrock formations are of value only for consideration as disposal reservoirs for highly concentrated industrial waste waters. The relationship between the static water level, high specific gravity of the native brines within the bedrock formations and the low specific gravity of the waste waters to be discharged make it theoretically possible for disposed waste waters to migrate upward by means of unrecorded or improperly plugged wells into the fresh water aquifers. The uncertainties related to natural fracturing between the various formations also cause a logical hesitancy on the part of regulatory agencies and consultants to recommend deep well disposal. For these reasons, waste water disposal into the bedrock formations less than 3,000 feet below the land surface is not recommended in this area. However, the bedrock formations below 3,000 feet are suitable for limited storage of waste waters.

INVESTIGATIONS

Studies of the industrial wastes involved detailed, in-plant surveys of the chemical character of the various waste streams and their treatability. As is often the case, the studies revealed that more than 90% of the waste water was cooling water which was unimpaired except for a slight increase in temperature. It was judged that this water was readily amenable to return to the ground for reuse. Approximately 5% of the waters were impaired and could be treated by available methods and discharged to surface waters. Approximately 2½% of the waste waters were of human origin and could be treated with ease. The remaining 2½% of the water was highly concentrated, highly complex industrial waste water. Further investigation indicated the latter could be treated by incineration and/or deep well disposal.

At the time of the study, the volume of the most obnoxious waste water totaled 5 to 10 gallons per minute. Projections based on the anticipated expansion indicate the volume will not exceed 50 gallons per minute.

Concurrent with the in-plant waste water investigations, treatability studies of the contaminated ground waters were conducted, and new potable and industrial water supplies were developed. The investigation of the extent of ground-water pollution and development of new supplies involved construction of a series of 1¼ inch diameter observation wells tapping the upper and lower portions of the sand aquifer. These wells permitted measurement of water levels, sampling of the ground waters, delineation of the area of the ground-water contamination and definition of the aquifer hydraulics. The latter data, together with the separation of the various waste streams, permitted construction of a new ground disposal recharge pond for the cooling waters and individual treatment of the contaminated industrial waste waters. The locations of purge wells, observation wells, production wells, cooling water return site and waste water ponds are shown in Figure 5. The basic head and ground-water flow conditions are also shown.

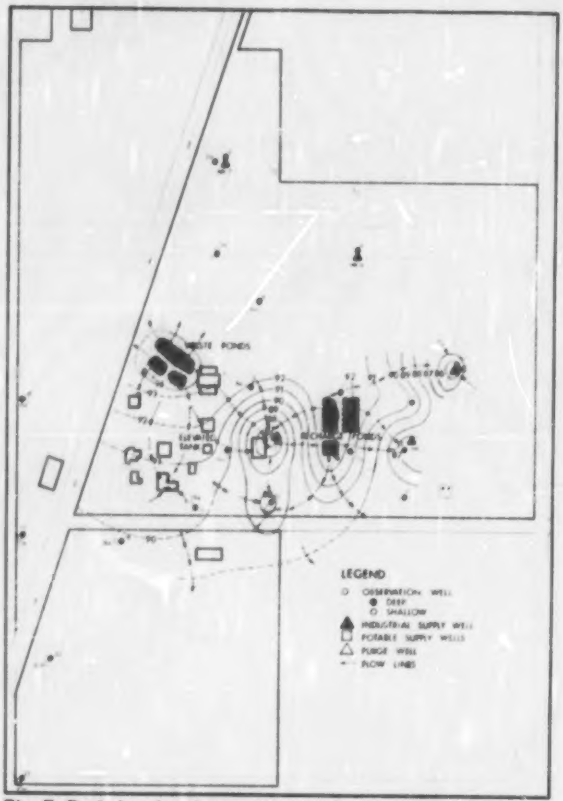


Fig. 5. Basic head and ground-water flow conditions.

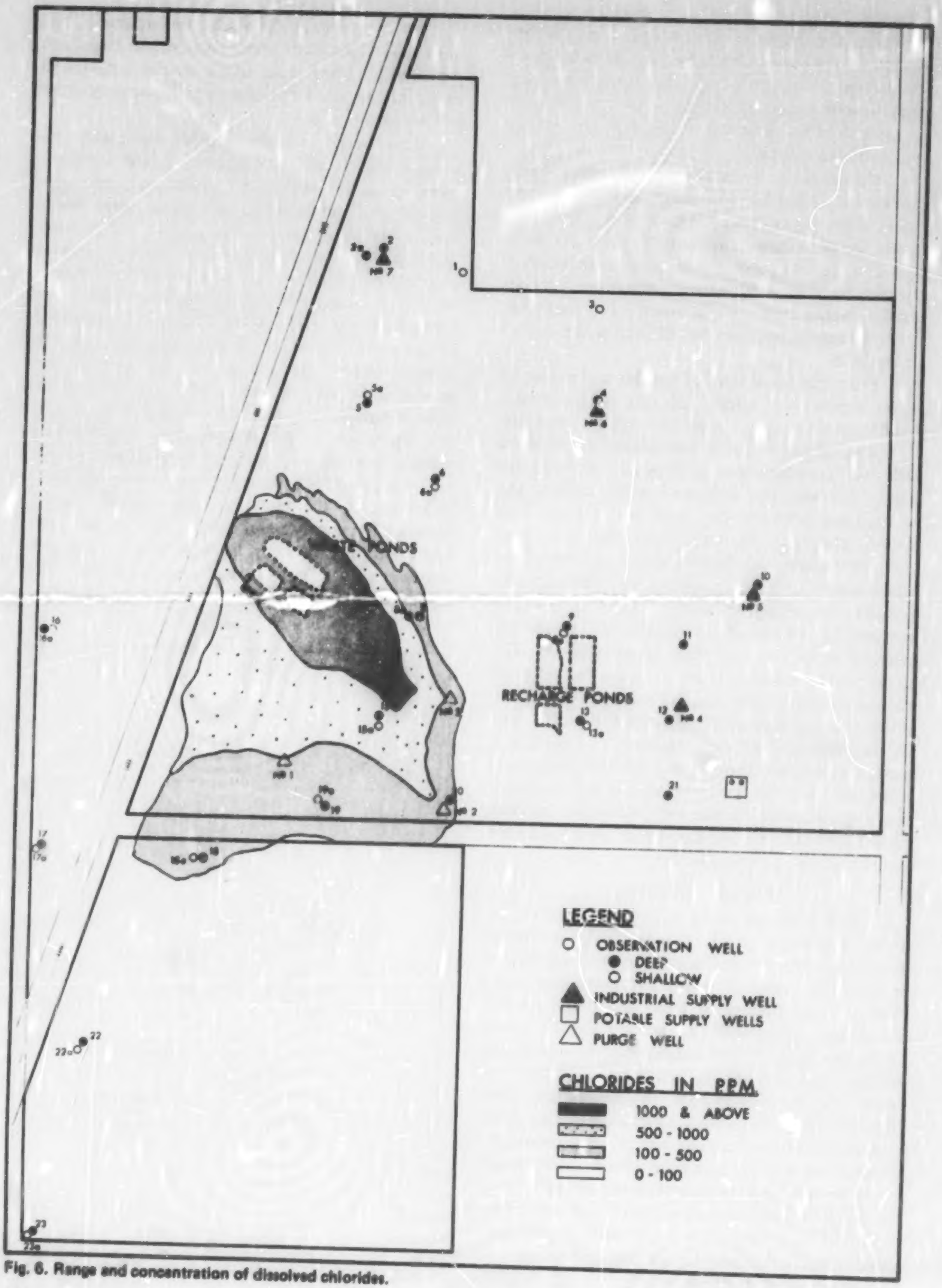

2a
2
№ 7
1
3
5a
5
4
№ 6
6
6a
WASTE PONDS
10
№ 5
16
16a
9
11
RECHARGE PONDS
15
15a
№ 3
12
№ 4
13
13a
№ 1
19a
19
20
№ 2
21
17
17a
18a
18
22
22a
23
23a
LEGEND
OBSERVATION WELL
DEEP
SHALLOW
INDUSTRIAL SUPPLY WELL
POTABLE SUPPLY WELLS
PURGE WELL
CHLORIDES IN PPM.
1000 & ABOVE
500 - 1000
100 - 500
0 - 100

Fig. 6. Range and concentration of dissolved chlorides.

Ground disposal of concentrated industrial waste waters continued after purging of the contaminated ground waters was instituted. The original production wells (1, 2 and 3) were used in the initial purging operations. Purging confined and removed the contaminated waste waters. These waters were delivered to the suitable receiving body of water until on-site waste treatment facilities were built. Figure 6 shows the range and concentration of dissolved chlorides, a parameter found to be proportional to the total concentration of contaminants. The Figure reflects the areal extent of the ground-water pollution and illustrates the combined effects of natural dilution and pumping. The greatest concentration occurs about the waste disposal ponds while natural factors disperse the contaminants away from the ponds. Purge wells 2 and 3 provided an effective barrier between the contaminated water and the fresh ground waters tapped by wells 4 and 5.

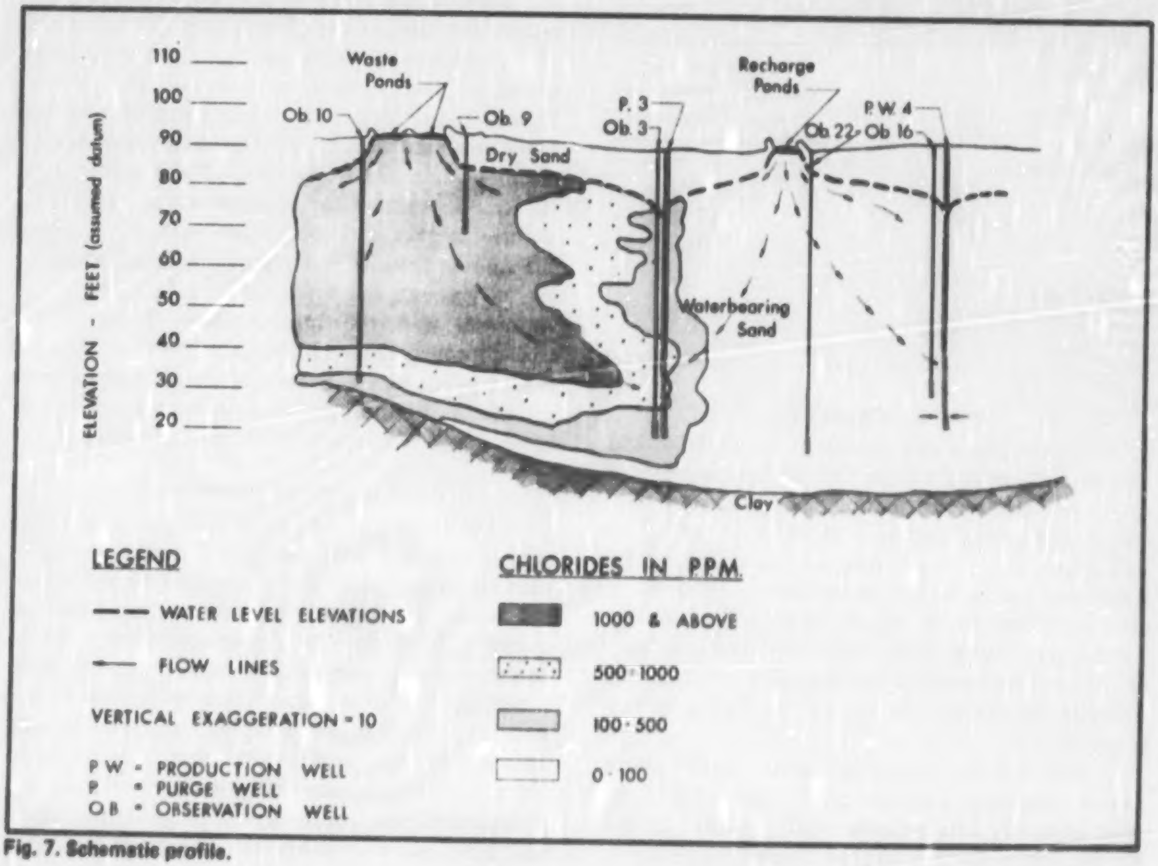
Figure 7 illustrates the vertical extent of ground-water pollution and the effect of the cooling water recharge ponds and purge wells. The flow of waste waters and their vertical distribution were governed by the natural recharge to the area and the effect of pumping. The top portion of the aquifer was the first zone to show improvement after cessation of disposal of wastes to the ground.

WELL STRUCTURES

The potable supply, industrial supply and purge wells were all constructed by the cable tool method of drilling. This method was chosen because efficient well structures could be accomplished with ease and economy. However, the economies and well efficiencies were balanced with the immediate needs for production capacity. The basic physical characteristics of the production wells are summarized in Figure 8.

Well No. 1 supplied the initial potable and industrial needs. The well is tubular, 6 inches in diameter, with 15 feet of screen. The screen was set in the lower portion of the sand aquifer bottoming at approximately 60 feet. According to records the well screen is a wire wound, silicon red brass screen with 0.010 inch slot openings designed for 50% retention of the formation. Based on subsequent wells of similar construction, the specific capacity of the well was estimated to be from 5 to 8 gallons per minute per foot of drawdown.

The construction of the many wells throughout the site revealed that the aquifer sands are



110
100
90
80
70
60
50
40
30
20
ELEVATION - FEET (assumed datum)
Waste Ponds
Ob. 10
Ob. 9
Dry Sand
P. 3
Ob. 3
Recharge Ponds
P.W. 4
Ob. 22
Ob. 16
Waterbearing Sand
Clay
LEGEND
WATER LEVEL ELEVATIONS
FLOW LINES
VERTICAL EXAGGERATION = 10
P W = PRODUCTION WELL
P = PURGE WELL
O B = OBSERVATION WELL
CHLORIDES IN PPM
1000 & ABOVE
500 - 1000
100 - 500
0 - 100

Fig. 7. Schematic profile.

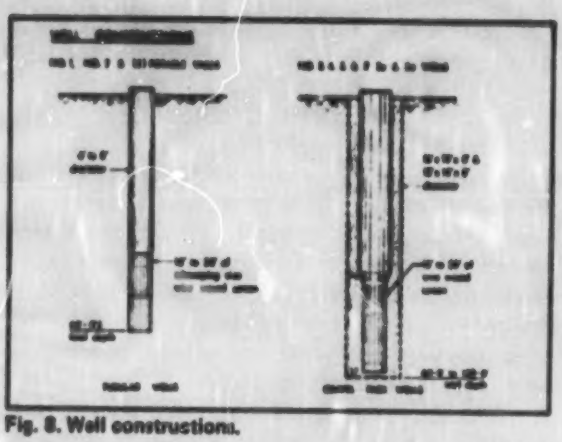


Fig. 8. Well constructions.

uniformly fine. This characteristic led to standardization on gravel pack type well construction. Wells 3 through 7, and replacement wells 2A and 3A are all gravel packed well structures of the type shown in Figure 8. The original wells 1 and 2 and the potable supply wells are tubular wells, also as shown in Figure 8. The potable wells and industrial wells 4, 5, 6 and 7 have met and surpassed the water needs of the company. The original yield characteristics, as specific capacity, is summarized in Table 1.

Table 1. Original Specific Capacity

Wells	*Specific Capacity (gallons per minute per foot of drawdown)*
Industrial Well No.:	
4	13.5
5	14.2
6	28.1
7	14.2
Potable Wells:	
East	6
West	6

WATER QUALITY

The original water quality of the shallow sand aquifer was approximately 110 milligrams per liter (parts per million) of hardness as calcium carbonate, 5 milligrams per liter of chloride, and 0.25 milligrams per liter of iron. These native ground waters are not as highly mineralized as ground waters elsewhere in Michigan. Even so, with time some deterioration in the production characteristics of the well by chemical precipitation of carbonate deposits occurs and occasional redevelopment is required.

The complex chemical nature of the waste waters originally disposed to the ground has not only adversely affected the quality of the ground waters within the area but has created maintenance problems with the purge wells. It is necessary to redevelop the wells as often as once a month. The wastes are more viscous than water, move slowly through the fine sand aquifer and continually plug the aquifer, gravel packs, well screen openings, pumps and pipeline facilities associated with the purge well system. The chemical characteristics of the waste waters disposed to the ground over the years in which this disposal method was used varied from moment to moment, day to day, and month month, according to the types of products made and the market demand.

The industrial waste waters vary in pH from extremely acid (pH 2±) to highly alkaline (pH 12±). Some of these waters are organic compounds. BOD and COD characteristics are also present and extremely variable.

Part of the fouling of the purge wells appears to be related to the interaction of alkaline wastes with the bicarbonate component of the natural ground waters. Such mixing leads to supersaturation with calcium carbonate. Precipitation of the latter within the turbulent flow regions of the well is natural. Organic residues are another cause of purge well fouling. Soil bacteria are suspected but unproven fouling agents.

Despite the complex properties of the waste waters disposed to the ground over a period of ten years, persistence and the application of hydrologic principles has assured recovery of the aquifer. Figure 9 summarizes this recovery. The contaminated ground waters have been steadily removed by pumping and diluted by natural and artificial recharge. Extraction of ground waters at a rate slightly in excess of the natural recharge confined the contamination and permitted flushing of the wastes through the soils and into the purge wells. As anticipated, the upper portion of the aquifer was improved first. The improvement of the zone is shown by well 7a. Natural recharge, coupled with the effect of pumping, drove the wastes to the lower portion of the aquifer as shown by well 19.

WELL REDEVELOPMENT

The fouling of well structures, particularly the screen openings and the gravel packs, result in marked reduction in the production capabilities of the wells. The loss of capacity and need for frequent redevelopment is particularly marked in connection with purge well systems. In that system, redevelopment is accomplished by various means such as air lift surge, pumping surge and jetting, assisted by the addition of chemicals. Various chemicals used include acids, alkalines, chlorine and phosphates. The more tightly plugged the screen and gravel pack openings, the greater the necessity

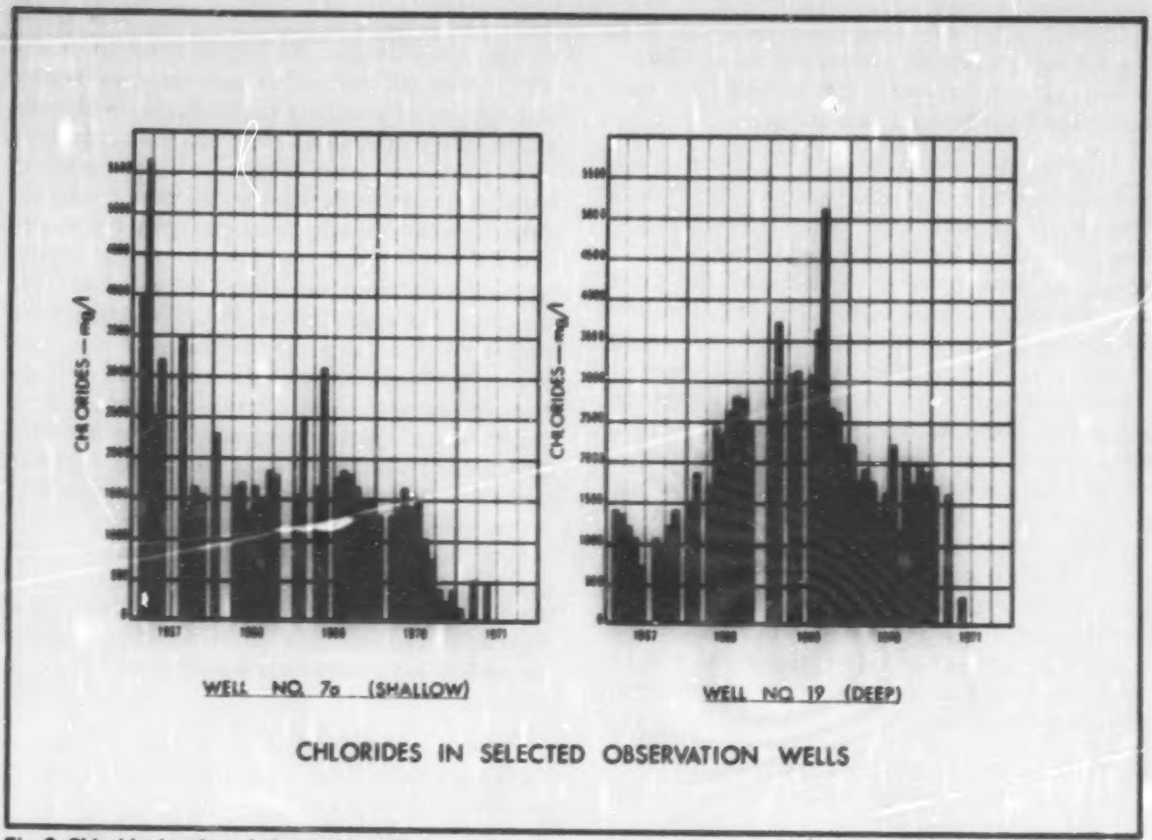


Fig. 9. Chlorides in selected observation wells.

to use several applications of chemicals and the most vigorous hydraulic surging procedures.

The purge wells tapping the ground waters of the highest concentration of pollution, require the most frequent redevelopment. Even so, gradual loss of capacity to yields of one-fourth to one-half the original specific capacity occurs. The less concentrated the waste handled by the well, the less frequent the need for redevelopment and the more successful the redevelopment. The potable supply wells and the industrial supply wells 4, 5, 6 and 7, all of which produce waters nearly the same as the natural ground waters, seldom require redevelopment. When redevelopment of these wells is required, it is rapidly accomplished by acidizing and surging with the pump, followed with thorough disinfection by chlorination.

CONCLUSION

The preceding has summarized the gross aspects involved in the continued use of a vital natural ground-water resource while simultaneously correcting a misuse of that resource. The multiplicity of interdisciplinary responsibilities was inferred more than described, but constituted a major contribution in accomplishing the end result.

The scientific principles, technical methods and skills associated with the location and development of a ground-water supply are equally applicable to the solution of ground-water contamination problems. However, the role of the geochemist and the sanitary engineer are more vital in the solution of ground-water pollution problems if successful recovery of the damaged portion of the environment is to be realized. For instance, the services of the geochemist are needed to assess the degree of hazard involved and the effect of contamination on the geologic environment. The services of the sanitary engineer are necessary for evaluation of alternate methods of treatment and the associated economics. Depending upon the characteristics of the geohydrologic environment and the nature of the contaminants, the services of other specialists may be necessary for a proper and economical solution. It is essential that all parties involved recognize that if man is capable of utilizing the many technical aspects of his environment, he is also capable of meeting the challenge of correcting the misuse of the environment.

DISCUSSION

The following questions were answered by Edward M. Burt after delivering his talk entitled "The Use, Abuse and Recovery of a Glacial Aquifer."

Q. *What is the temperature of the water in the recharge ponds and what effect did these ponds have on the pumped water temperature from the two wells immediately east of those ponds?*
A. The temperature was checked and the effect was thoroughly investigated. I am sure all of you are aware of the problems inherent in the operation of any type of a facility, whether it's water or waste water treatment. It seems that we human beings take the path of least resistance. If a gallon of water will keep a reactor cooled to the proper temperature, then the maximum hydraulic flow will do even better. The average flow of cooling waters vary from 0.5 to 1.0 mgd. The temperature of 90% of this flow does not change more than 2 or 3 degrees F. By the time the recharge water reaches Wells 4 and 5 and is blended with fresh ground water, there is no measurable difference in temperature between those two wells and samples taken from Wells 6 and 7.

Q. *You mentioned that in order to receive a permit from the Water Resources Commission, the industry must comply with certain regulations? What are these?*
A. Michigan does not have a rigid set of regulations, but rather establishes specific criteria tailored to each individual site. These standards are set in this manner. Any industry that wishes to make use of either the surface or ground-water resources in the State must apply for a permit. This application must indicate the nature of the business and the waste they wish to discharge. The staff of the Water Resources Commission confers with other State agencies, such as the Michigan Department of Public Health and the Geological Survey, and together they develop a set of standards based on existing uses of the particular water resource in question. The most common limits imposed pertain to pH, BOD, COD, solids and specific elements.

Q. *Since the pollution showed up after a few years of operation, were the regulations given serious consideration by the industry prior to the building of the plant?*
A. This question precedes our involvement in the project, but our experience with the firm indicates that they have always given serious consideration to pollution problems, both real and potential. From what we have ascertained, the problem evolved because a detailed study of the ground-water hydrology was not originally required, therefore was not originally conducted. Another important consideration is the fact that between the time the plant was built and the time the problem was discovered, the types of products and processes employed changed. The regulations under which a discharge permit is issued are not like the law of the Medes and Persians—they are just the opposite; they are in a constant state of continuance. This is reasonable because, in establishing regulations, it is not possible to stop time. Each time a manufacturer considers the addition of a new product that introduces a new waste, it is necessary for the firm to apply for an amended order and the review process is repeated. This is the manner in which the presence of a problem was discovered.

Q. *What was the character of the material clogging the purge wells? Was it comprised of corrosion products, organic growth, etc.?*
A. That's the $64,000 one! Let me describe what happened. When the redevelopment of the wells was attempted, the greatest problem occurred in the pump impellers. As in all situations of this type, the first step was to remove the pump. The contractor's report indicated that after the bowls were disassembled, cleaning could be accomplished most efficiently by allowing the material to dry and then to remove it with chisels. Soaking in acid or alkalis was partially effective, but it made quite a gooey mess. There have not been complete analyses made of the composition of the material. The reason a complete analysis has not been made is that over the years of plant operation, varying quantities of many different types of waste have been produced. As a result, during a given time interval today the waste extracted will reflect those products of several years ago, but next month the waste will reflect a different combination of products and the composition of the extracted material will be entirely different.

Bull Session 4—Aquifer Protection and Rehabilitation

Session Chairman: Leslie G. McMillion, Geologist, National Ground Water Research Program, Environmental Protection Agency, Robert S. Kerr Research Center, P. O. Box 1198, Ada, Oklahoma 74820.

Leslie G. McMillion, Lead Bull:

Our session is "Aquifer Protection and Rehabilitation." All of the speakers of this session are present; they are Ed Burt, Ken Schmidt, and James Waltz. Also, Tom Ahrens is sitting in to answer questions that might be asked on the topic on which Joe Mogg was to have given a paper this afternoon; as you are perhaps aware, Mr. Mogg could not attend the Symposium and consequently he did not make his presentation.

This afternoon we received more questions concerning James Waltz's talk than James was able to answer during the discussion period that followed his talk. I have these unanswered questions with me, and there are about a dozen of them. I hope we will have time to enter these questions into the record of this bull session.

I appreciate the excellent attendance tonight. The subjects are excellent, and I surely anticipate lots of spirited and interested discussions. We are ready for your questions and discussion, and we certainly invite your participation.

Steven N. Goldstein, Mitre Corporation, McLean, Virginia:

Mr. Schmidt, we have a great deal of interest in the technological opportunities that individual home sewage disposal systems might offer. With respect to coming up with an optimal national plan for sewage treatment, there are quite obviously areas where septic tanks and other individual systems are very competitive and a better choice than centralized sewage collection systems. Of course, quite the opposite holds true in densely populated localities. It's most important then that proper septic tank and other individual system practices be reintroduced as opposed to the current situation where many builders just dig a hole and throw them in the ground and the things fail in 5 years, 15 years, or something like that. So, we've been studying this problem for the Office of Water Programs of EPA and one of my reasons for coming to this Symposium is to get a better feeling for how the people who are actually doing field work in water resources regard these systems. Could you comment on what you regard to be some of the future problems in this area of individual home disposal systems on the basis of the work you've done in the Fresno area?

Kenneth D. Schmidt, Harshbarger and Associates, Tucson, Arizona:

Organic nitrogen and ammonia nitrogen, which occur in both sewage effluent and septic tank effluent, can potentially form nitrate. In the case of septic tanks the conditions are generally more favorable for conversion to the nitrate form. This is due to the fact that the waste is disposed of over a large area and anaerobic conditions don't tend to develop as readily. Under anaerobic conditions, the nitrate may never be formed from the other nitrogen that forms. Also, denitrification may be lost as gaseous forms. More control of the nitrate situation in ground water should be possible with centralized sewage treatment facilities. However, each site must be carefully studied. The waste disposal operation, the soil, and the ground-water conditions are key factors.

There are areas near Fresno today where plans exist for new septic tank developments in the foothills. It is obvious from previous studies that the foothill area has generally poor aquifer characteristics. The aquifer is thin, the transmissibility is low, and locally major faults separate the developments from sources of recharge. Thus, these areas may be unfavorable for waste disposal of this type. However, in favorable areas, properly constructed septic tanks and disposal systems will be practical and not harm the ground water. In the Figarden-Bullard Area, septic tanks have been used for 20 years. Yet, only 2 wells have ever had nitrate contents over 25 ppm. Thus, in a favorable environment, if the wells, septic tanks, and septic tank disposal systems are constructed properly, a nitrate problem may not occur. Similarly, biological contamination may also not be present.

Hank Baski, Wright Water Engineering, Denver, Colorado:

We have a pending water quality study of ground water in an area where nitrates have been measured up to 50 or 60 ppm. Upstream from the problem site there's a municipal sewage treatment plant with secondary treatment, and some people say that the sewage plant is going to contribute nitrates which may enter the aquifer. Do the secondary treatment sewage plants actually take out nitrate?

Kenneth D. Schmidt:

As far as the amount of nitrogen that enters and leaves a conventional plant you have to remember it's not all in the form of nitrate. We're usually talking about the sum of organic nitrogen, ammonia, and nitrate. Most conventional plants convert some nitrogen to the nitrate form and also remove some organic nitrogen. Thus, total nitrogen is usually significantly lower in the effluent than influent. I seriously doubt that besides settling out of solids there is any drastic difference between the influent and effluent. I think the real opportunity to control nitrogen occurs after the effluent is discharged to ponds. Recent studies have shown that by controlling factors such as pH and temperature, loss of ammonia from ponds can be enhanced. Nitrate contents of 50 or 60 ppm would be expected near sewage treatment plants. Most sewage effluent contains from 25 to 30 ppm total nitrogen. If all of this nitrogen was converted to nitrate, concentrations exceeding 100 ppm could occur in ground water near sewage plants.

Edward M. Burt, Williams & Works, Grand Rapids, Michigan:

This nitrogen discussion is interesting. We're doing many waste water treatment projects in Michigan that involve oxidation lagoons and spray irrigation. Concerning oxidation ponds or lagoon systems, we have built over the years a number of ponds where the first cell was anaerobic on the bottom and aerobic on top and then the following cells were totally aerobic. The initial pond was designed and built so that the basal portion of the pond operates under anaerobic digestion and the surface operates under aerobic digestion which is typical of oxidation ponds. The balance of the ponds following this are oxidation ponds of aerobic digestion. Both types of digestion accomplish things that are desirable and that's why we have used them as raw sewage or initial ponds, though this is no longer allowed by the Michigan Department of Health. We designed some of these and got very high degree treatment. There's a great deal of discussion and evaluation in Michigan by the Health Department; and some people, including some sanitary engineers argue that oxidation lagoon systems without the anaerobic facility or with it accomplish what is commonly known as secondary degree sewage treatment. This process then is comparable to a mechanical activated sludge plant. Along the idea of nitrogen removal, this past winter we obtained permission from the Michigan Department of Health to experiment and have winter drawoffs. The normal procedure in Michigan is that you store and discharge in the fall and in the spring. This past winter the Health Department gave us permission to use continuous discharge from about 9 ponds. And while we had ice cover we drew off from these at a regular rate while not breaking up the ice cover, and we had significantly higher removal of the nitrogen than has been accomplished by ponds or secondary degree treatment. We don't have any conclusions but the suspicion is that the oxidation ponds rely upon algae which feed on the nutrients in the waste water and in the winter the algae are not as active as in the growing season; therefore they die and go to the bottom as sediment with the result that under the ice we pull off very high quality waste waters.

M. G. Croft, U. S. Geological Survey, Bismarck, North Dakota:

I'd like to direct this question to Ken Schmidt. In your discussion this afternoon you mentioned a background nitrate count of several ppm in the ground water. I was wondering if you'd care to comment on the origin of this nitrogen.

Kenneth D. Schmidt:

As you probably know, nitrate has been analyzed from samples of the Kings River and the San Joaquin River, and it often ranges from 1 to 3 ppm. Evaporation would slightly increase this content before percolation of surface waters to the water table. However, I do not envision the 6 or 7 ppm as all natural, but rather background to the urban area. Flow net considerations and travel times in ground water suggest that much of the urban ground water was actually beneath agricultural lands several decades ago. Thus, some of the background content could have been supplied by agriculture. Agricultural lands surround the urban areas, but were probably not heavily fertilized prior to 1940.

Another natural source besides runoff would be related to soils near the foothills, northeast of Fresno. Stout, Burau, and Allardice point out that areas with a Mediterranean climate are favorable for natural nitrate accumulation. Strahorn, who did the early soils work of the Fresno area, noted that high grasses grew on the alluvial plains. In areas of a Mediterranean climate, precipitation occurs in the winter, and natural plants grow and take nitrogen out of the atmosphere. In the hot summer these plants die and most of the nitrogen remains as residue in the soil. This nitrogen is then converted to nitrate by bacteria. With the coming of the next winter, abundant rainfall leaches the nitrate past the root zone and into the ground water.

The Agricultural Research Service has done studies on a small basis in eastern Fresno County and has found natural nitrates. Near the east edge of the San Joaquin Valley rainfall may approach 16 inches per year and vegetation may be more plentiful. Natural nitrates have been found beneath dry farmed areas of eastern Fresno County and are apparently related primarily to the soil. The soils themselves have some nitrogen even though they are very low in organic matter. They contain something like 1,000 ppm of nitrogen on the average. However, there is no guarantee that any of this nitrogen can be converted to nitrate and leached to the ground water. It is obviously a source worthy of consideration.

Robert E. Pendergast, Geotechnical Engineering Corporation, St. Paul, Minnesota:

My question is with regard to installing observation wells, sampling wells and techniques for sampling. I'm aware of various methods that can be used, but I'd like to take advantage of your expert knowledge on the state of the art. What is the most efficient method for installing the well and obtaining the samples for reliability and accuracy on a normal industrial job, rather than on a long-term research study?

Edward M. Burt:

Let's talk about observation wells—monitoring wells in broad generalities. I will make reference to the industrial investigation that my firm had going for 15 years, and the work we've been doing to correct the situation that I discussed in my paper this afternoon. Since the aquifer of concern in my paper consisted of unconsolidated sand with relatively good homogeneity throughout the water-bearing zone, we were able to use the auger machine for installing 1¼ inch diameter casing in our observation wells. The auger that we used was a continuous worm auger that stays open with rotation. We did not find it necessary to use mud to get good results. On the bottom end of the 1¼ inch casing we used standard household well points of 24-30 inches long. In some instances we went to 5-foot well points. I mentioned that we preferred to sample the upper 15 feet of the formation and the basal 15 feet; and this sampling approach was a judgement decision based on the geohydrologic conditions of the site and the soil conditions.

In connection with the construction of waste water lagoons, oxidation ponds, and spray irrigation, we again tailored the method of investigating for establishing monitor wells because there has to be an initial investigation to establish that the soil conditions and the geologic conditions are proper, and there has to be a continuing monitoring program established, especially in connection with irrigation projects. We normally go in with the auger machine first. However, we utilize the readily available well records; for several years the water well drillers in Michigan have been licensed and they are required to file logs; and, in addition to this, the filing of logs on oil and gas wells are required. We take this information and go on the site and make preliminary estimates of the direction of ground-water flow and what the basic hydrogeologic conditions are. We take an auger machine and check out our original ideas, and then we make a predesign of how we are going to analyze these conditions and how we are going to finalize the monitoring well system. In more complicated geologic situations we go to either cable tool drilled wells with casing or rotary drilled wells with mud and we use electric logs. In using cable tool drilling, we normally collect our geologic samples at 5-foot intervals and at each change in formation. The final well for monitoring is really designed to the geologic conditions and the use of the site. We establish the initial ground-water gradient and we have to set up sufficient observation wells to permit continuous monitoring of this by the people who operate the facility.

George Taylor, U. S. Geological Survey, Washington, D. C.:

At the present time in West Pakistan, there is quite a bit of controversy going on over the fall-off in yields of wells that have been put down during the last 8 years, using fiber glass slotted pipe. They have a standard well design. I'm sure Mr. Ahrens is familiar with this area. I understand he's a well design expert, going by reputation. He doesn't know me but I know him. I wonder if he could comment on the relative importance of the chemical precipitation of carbonates in the filter pack around these fiber glass slotted casings as against the physical clogging of the slots through incomplete development.

Thomas P. Ahrens, U. S. Bureau of Reclamation, Denver, Colorado:

I'm talking pretty much from scuttlebutt. I have tried to get some definite information and have talked to several people from Pakistan when they were in the office over the last few years. None of them know anything about it. I was fortunate enough to have a few old friends who were over there working for contractors; and from the letters I have received from them, I have been reading between the lines. When Harold Smith was there the first time, they put down all these wells and tested them, and they turned out to be 2 or 3 second-foot wells, but it was 9 months before they got the pumps to put in. When they put the pumps in they turned them on, and they sucked air. They tried shooting them with primacord; that would bring them back for about 2 months and then they would go out again. So they pulled some of them and found a combination of sulfate reducing bacteria and encrustation; thus, what you had was the corrosion products mixing with the encrustation products to give a complete blocking of the well in a couple of months. So then they started out on this fiber glass, reinforced epoxy. The prime contractor on the job called me and wanted to know what I thought about it, and I said we had been looking at it for years and were afraid of it. He said they were going to use it over there and asked me to recommend a minimum wall thickness. I said I wouldn't go less than ¼ inch. So they went in with .180 inch for the casing and .200 for the slotted pipe. Well, from the stories I've received from the contractors over there, they can't develop those wells completely. If they go in with air or with a surge block, they collapse. So what they do is merely go down to near the top of the screen and overpump them. They are running anywhere from 60 to 90 feet of perforated casing in those things and all of you probably know that when you develop a well by overpumping all you do is develop possibly the upper quarter or maybe third of the perforated section. The rest of it—nothing happens to it. I have always suspected that the change to the glass reinforced epoxy would cut down on the corrosion; in fact, it would eliminate the corrosion. But I always thought that the encrustation would still occur but that it would be extended over a long period of time. Now you've provided the first concrete evidence I've heard that this is probably happening.

George Taylor:

I think there is still some controversy over this point; as a matter of fact I'm in the minority. All I know is also hearsay. I've been in touch with a number of people, and we have a man still out there. I think everybody agrees that the fiber glass is essentially inert. There are no corrosion products forming directly in the slotted pipe or in chemical combination with the material. But, these wells have fallen off in yield. I understand that television cameras have been lowered down some of these wells and they have been able to look at the insides of these wells. They're finding that there is a little bit of slime on the inside which may be a result of bacterial action. I have the feeling that a lot of the precipitation of carbonates may be still occurring in the filter pack outside the casing contributing to the fall off in the yields. There is some evidence in some of the wells that there is quite an accumulation of material in the bottom of the well that has come through the slots, fine material.

Thomas P. Ahrens:

Just sand? Is it actual material or what?

George Taylor:

Well, apparently, yes, sand has come through. Through, as you point out, incomplete development, you see. So it may be a combination of these things but most people I've talked to don't give much credence to this idea that there is actually carbonate precipitation taking place in the filter pack. I understand that much of the filter pack material they use is quite high in carbonate material, native carbonate material.

Thomas P. Ahrens:

If your screen was not developed for its entire length, you had your concentrated flow at the top where it was developed and you probably run into inflow velocities there, possibly a few feet per second. So you'd have an ideal situation for the deposit of carbonates if they were in there. Now this other slime you mentioned. Do you know if they are pulling any of those wells down below the top of the screen?

George Taylor:

I really don't know. I understand they do have high drawdowns in some of the wells.

Thomas P. Ahrens:

When the water levels are pulled down and you get *Crenothrix*, *Leptothrix*, *Gallionella*, and all of those, they'll get down in there and every time you pull that down a little bit they'll start growing. And, as they grow down, they block it; the water table or pumping levels keep going down, so they just keep moving on down the screen. That might account for some of that slime you mentioned.

George Taylor:

I understand they only lowered this thing in one or two wells but they did find some kind of growth that seemed to be a precipitate or slime inside the casing.

Thomas P. Ahrens:

Incidentally, do you know if they can pull that fiber glass pipe or will the joints pull apart when they try?

George Taylor:

Well, that's another problem. They did, I understand, get one out more or less intact, but it was clean. I mean they found no evidence of slime or precipitates.

Thomas P. Ahrens:

Well, it's so slick that I think if you did have any carbonate deposits on there, just pulling it out would probably strip it off.

Jerry Frick, Walkerville Well Drilling Co., Walkerville, Michigan:

I'd like to ask Mr. Ahrens if he has any information or experience on the relationship between intake velocity and buildup of encrustation?

Thomas P. Ahrens:

Let us say "no observation." We have some beautiful examples at the office that I could show you of high intake velocities and very high corrosion; and also some similar information on encrustation but I have just observed these latter myself. Now we just use a 10th of a foot per second intake velocity. We have never had any bad problems with that criteria except when we were in a terrifically corrosive aggressive water; but the problems would have occurred, I think, whether we would have been pumping or not.

Edward M. Burt:

I've played with wells too, and so I'll share some top of the hat recollections. I'm not sure of the details of the construction of these wells, but I have been involved in experiences with bacterial plugging where the best result on redevelopment was not accomplished by chemical treatment but by heavy chlorination. Another slimy sort of thing that we can run into is, for instance, in a double screened well, with the suction intake set down in the screen or between the two screens, when you pull the pumping water level down below the upper screen you cause a cascading, you have a beautiful in-the-well iron precipitation plant. And this will foul them very rapidly, quite completely. As a practical guide, I haven't used it too much, but by my experience I'm convinced that you get plugging beyond the screen face, and perhaps beyond the gravel pack. A lot has to do with the geology of the formation. When we talk about gravel packs it's a misnomer to say gravel because it is really filter sand in wells that are developed in a silty, fine sand formation. The City of Kalamazoo recently determined that the distance out to where the plugging extended in their wells was between 7 and 9 feet. These determinations were made by running a step test in reverse (that is making an injection test) and calculating the volumes and decrease of injection rates.

Thomas P. Ahrens:

You mentioned a heavy chlorination. There's been quite a bit of research done on that and one item in particular, that being sulfate reducing bacteria. It takes at least 400 ppm and about an 8-hour contact to kill sulfate reducing bacteria. We started out using the HTH calcium hypochlorite but our labs called us on it because when you run over 300 ppm on HTH you start precipitating calcium carbonate. So we have switched over now to Clorox and 2 gallons of Clorox to 100 gallons of water in a well will give you about 1,000 ppm and we figure we're getting a certain amount of dilution so it's probably coming down to around 400 ppm.

George Taylor:

How long would it be do you think before this bacteria would again build up to the concentration where they would cause a plugging problem?

Thomas P. Ahrens:

We have a terrific problem with that down in Wellton Mohawk in Yuma. We started out sterilizing those wells and we found out right after sterilization we got a negative reading on our sampling for anywhere from 2 to 6 weeks, and then it would start coming back. I think that there are just so many little crevices and cracks and places for a bug to hide in a well that you can get 99 percent of them but that 1 percent that are left are right back building families as soon as the stuff is gone.

Leslie G. McMillion:

Tom, what is your procedure on taking samples in checking for bacterial growth?

Thomas P. Ahrens:

That I will have to claim ignorance on, Les. We turned that over to the microbiologists and they would go out and pump the well. I do know they had some sort of a filter that they passed the water through, and collected so much water or passed so much water through it and then, as I understood it, the colony actually grew on the filter. I can get additional information for you if you'd like it.

Leslie G. McMillion:

Yes, thank you. I will contact you later for the information.

Steven N. Goldstein:

Maybe I can clarify that procedure somewhat for you. I'm no expert in the area but I have gone through some of those tests. The filter in question is probably something like a membrane filter with pore size small enough to trap bacteria. What you do is take a measured quantity of liquid, say 100 milliliters, draw it through on the vacuum, the bacteria then will not pass through, they will be caught on the filter paper and then you transfer the filter paper to the top of some kind of a nutrient medium like an agar gel. The nutrients can diffuse up through the filter and the colonies can begin to grow. The idea is that each viable bacterium or other microorganism that can live in that medium will begin to divide and form colonies and after a suitable amount of time you can actually see the colonies as little spots on the filter paper. Now what you're getting from that kind of a reading is called a total viable count. In other words, how many bacteria or other microorganisms did you have in that initial sample that were viable enough to form a colony. But at that particular point you have almost no idea as to their identity, except for the fact that you may know something about the medium which you are using to feed them and you know that various media are selective for various species. But you only have a rough idea of what they might be.

Alfred H. Harder, U.S.G.S., Boise, Idaho:

Are these bacteria indigenous to the aquifer or are they exotic?

Thomas P. Ahrens:

I was just going to ask Mr. Goldstein if he could answer a question on that. One of the bacteria we're having trouble with is *Desulfovibio*, a sulfate reducing organism which, by the way, causes tremendous problems in pipelines too. But from what I've been able to read concerning the pipeline problem, the *Desulfovibio* generally don't occur below a depth of 10 to 12 feet. But here we're getting them down in wells that are 125, 150 and 200 feet. I've had more darned arguments with various people, and they'll swear up and down they are in the aquifer. But if you check the size of the things, they are bigger than any of the pathogenic bacteria which are filtered out in the aquifer in a relatively short distance. How could these larger ones travel through and affect the whole aquifer? At Wellton Mohawk we have two wells put down by the same contractor, ¼ mile apart. One of them has been in for 14 years and has never given any trouble at all, the other went out in 18 months. Now if it's in the aquifer, they both should have gone out.

Steven N. Goldstein:

I can't give you a direct answer but maybe I can bring to light a few things which might add to a total picture. First of all, as far as travel of microorganisms in aquifers are concerned I have no first hand experience. I've done some reading on the subject lately. This was mainly investigations done on the Santee project in California, and if I can recall the details correctly there were some movements on the order of 200 feet, even 400 and 600 feet where the bacteria were picked up in sampling wells. I believe the situation here was one of a saturated aquifer—thus, travel through saturated zones. I'm also led to believe, however, that if you're not going through a saturated zone that most of the things are usually filtered out in the first 7 to 10 feet. As far as the size of the bacteria, I don't think that they vary that much in size. I may be wrong, but I don't think the size variation is very great. The other thing about bacteria is that they are all over the place. They're all over your skin and all throughout your body; and you couldn't live without some of them. They are on the floor of the ocean; most of them are concentrated in the first millimeter of sediment there. They are on the floor of the bays, and they are in the air. Bacteria have even been found in the upper atmosphere where it was thought there were no living forms. So you just can't get away from them and about all you can hope to do is reduce their concentration in a clean room so that the chances of one of these things falling and contaminating some research work you're doing is kind of nil. I imagine that they'd be fairly ubiquitous in soils too. It only takes one of these things to get something going, one or a very few. And you never kill them all off. The dose of antibiotic that is now necessary to kill off the gonococcus bacterium that causes gonorrhea, has gone up quite significantly because people were getting a dose of antibiotic that would kill off 90 to 99 percent of the population, and those which weren't killed off were the highly resistant ones. Then, of course, these things build up in the population and it will take a little more, and a little more and then a little more antibiotic each time, and so this can now become a significant public health hazard.

Another thing which is very interesting is the work on clogging that was conducted by Thomas, Schwartz, and Bendixen at the Robert A. Taft Sanitary Engineering Center in the middle 60's. They were studying the clogging of soil by secondary sewage effluent with lysimeters. They reported that most of the soil clogging occurred in the first centimeter at the soil-water interface and that severe clogging was associated with anaerobic conditions in the zone of clogging. The black color of a slime which developed at the soil-water interface was due to the presence of ferrous sulfide but the ferrous sulfide did not contribute measurably to the clogging mechanism. What happens is that ferric ions are reduced to ferrous ions by anaerobic bacteria. In a similar manner, sulfate is reduced to sulfide and the reduced forms combine to precipitate out as ferrous sulfide. Addition of acid or restoration of aerobic conditions rapidly eliminate the ferrous sulfide but the layer remains clogged to the same degree. It takes a longer time of drying under aerobic conditions to destroy the surface mat and to eliminate much of the clogging agents. In summary, the clogging mechanism in applying sewage to the soil through seepage beds, trenches, etc., is probably due to development of anaerobic conditions right at the soil-water interface. It has been reported by Mitchell and Nevo that accumulations of bacterial polyuronides or polysaccharides in the slime layer may be a major cause of the clogging. I really don't have any idea what happens in the deep wells, but it may be some of these surface phenomena that occur in seepage beds, trenches, etc.

Hank Baski:

I'll comment some more about bacteria. Here north of Denver we've worked on Fox Hills wells that range in depth anywhere from 700 to 1200 feet. We chlorinate these wells since chlorination is required by the Health Department. We try to have it in the well itself in order to prevent any bacteria from becoming excessive. It sounds as if we've got bacteria all over and during normal construction of a well. It would be impossible to prevent bacterial contamination. We found that chlorination in a well seems to keep a well in good shape. One possible solution in an area which has a problem is you just chlorinate whenever you pump so there is a residual chlorine. However, we've got one water Association which is against well chlorination. It's an odd situation, too, because they have a well which has a problem; sometimes it will pump out a slime which may be 5 or 10 percent of the water volume. I've never looked at the stuff pumped out, but they say it looks like fish eggs when coming out of the well. Pipes were coated with it when they pulled the pump. It seems that preventative maintenance in the nature of chlorination of the well would be a possible solution to these problems.

James P. Waltz:

What is the concentration of chlorine that you use in this routine treatment of the Deep Fox Hills wells?

Hank Baski:

It would be in the order of 1 ppm.

James P. Waltz:

What is your procedure for introducing the chlorine into a well?

Hank Baski:

Whenever the pump operates, it's designed to operate so the pump starts, the solenoid switch opens, you've got the pressure differential of the water pressure at top, just run it through the chlorinator and have a plastic pipe, ½ or ¾ inch which goes down. We've found it's best to have it go below the pump because sometimes the stronger chlorination solution if operators don't watch it can corrode the pump.

Thomas P. Ahrens:

We had a somewhat similar problem at the Brush substation at Beaver Creek. What we did was just take a cylinder of chlorine and about an eighth-inch diameter pipe and ran the pipe clear down to the bottom of the well, then we just cracked that cylinder and we let the chlorine bubble up. However, it wasn't for potable use, it was just for cooling water; but it did lick the problem.

Alfred H. Harder:

I have three things that I'd like to get some comment on. One is, I had an opportunity to work on a well from the very first time it was constructed and the water superintendent of this town was very concerned about an iron problem in his wells so he decided that iron bacteria were being introduced. So from the initiation of drilling of the well he had everything chlorinated. The workers wore gloves that they had to dip in chlorinated water, the drill stem was chlorinated, the mud was chlorinated, and everything was chlorinated. He still had iron problems in his well. I wondered if any of you had ever heard of such an approach as this and how it had come out. The other thing I had an experience with was on an industrial well in which the pump failed. They pulled out the pump; it had a stainless steel pump shaft then, of course, but around the pump shaft were layers of encrustation. The peculiar thing was that it was layered—light layer, dark layer, light layer, dark layer, etc. So I cut this off and preserved it, and my first reaction was that it must be 3 years old, and sure enough in checking with the company the well was 3 years old. It might be a result of water level fluctuation. But strictly speaking, water level fluctuation didn't seem to make a whole lot of sense. So then I decided, well, it must be they pumped more water in the summer than they did in the winter and maybe this caused the encrustation. But I'd like to know if any of you have heard of a similar occurrence, and what would be your interpretation of a multilayer deposit like this? The stainless steel was not pitted, it was just as clean and nice as if it had just arrived from the factory. The third thing I'd like to mention is that I am really interested in comments previously made regarding the relative size of iron bacteria; I believe somebody said that all bacteria were about the same size while someone else said that iron bacteria were larger than others. I know nothing about bacteria, really. I'd like a little elaboration on this because what I'm immediately thinking of is if the bacteria are all the same size, they must be able to move through the aquifer. How do they move away from the well?

Thomas P. Ahrens:

Well, I'm not a bacteriologist, I'm just talking from what I have deducted from my actual field observations. I think a lot depends on the nature of the aquifer under study. If you have an aquifer consisting of clean well-worked gravel, for instance, I think bacteria can travel for miles in it. But where you have a fine sand aquifer, and as Mr. Goldstein mentioned, you are making tests under unsaturated conditions, I think they will find that the bacteria are filtered out rapidly. Now, looking at one of your other areas of concern—the deposition of alternating layers of light and dark substances (perhaps organic substances) in wells—I have never seen anything quite like that in wells. I have seen it where you had the filamentous iron bacteria where it just looked as though somebody had taken a bunch of horse hair and wrapped it around the shaft.

Steven N. Goldstein:

Just one comment about the size of bacteria. I guess a lot of them will range anywhere from a micron up to 10 microns; there might be some that are even bigger. Some will travel in groups attached in a long chain, so that will be even bigger. Some bacteria have flagella that make them capable of motion under their own effort. There are all kinds of different conditions. When you're talking about something the size of the 1 to 10 micron range and then you look at the size of the pores in your aquifer to see what can get through, I think also whether it is saturated or not makes a difference. So when I said they are all about the same size I mean "sort of in that range."

Thomas P. Ahrens:

Along with what Mr. Goldstein said, I did check on sizes of sulfate reducing bacteria. The average size was about 1.7 microns. Most pathogenic bacteria are a little less than a micron. That's what I was referring to when I was talking about sizes.

Hank Baski:

Speaking of iron in water, I don't believe everything is known about it yet, especially with respect to well water. I've personally had experience with two cases—one a Fox Hills well near Denver where the wells when new do not have any iron in the water and perhaps 1 to 5 years later will develop iron and get progressively worse. I am inclined to believe from reports of other people that something in the water is converting the casing to soluble iron in the water. They ran a pumping test and there was about 8 ppm iron; then they heavily chlorinated it, pumped it again, and found the iron content had dropped to about 2 ppm, which is quite a drop. The other situation involves Dakota wells in the Pueblo, Colorado, area; these wells are all characteristically high in iron content.

Let me make reference to a well in this area that I field tested last summer; I checked the iron content of the well water as it came out of the well. The iron concentration of the water varied as we varied the pumping rate of the well. We discovered that the water produced at the higher pumping rates contained lower concentrations of iron than did water which was obtained from low pumping rates. Thus, the differences in iron concentration could be due to the contact time, which the water has in the well casing. It should be noted that the water was warm, being almost 100 degrees F, casing string was 1800 feet long, pump was set at probably 400 feet; so it had a difference in travel time and distance sufficient for that water to pick up iron from the casing. I'm seriously thinking of trying to case the next well we drill in the Pueblo area with fiber glass casing, and see what the difference in iron content is.

Edward M. Burt:

I agree with the statement that not everything is known about iron. When you start calculating the pounds per day produced by a well and how many pounds of iron you've got in the casing, look out!

Jerry Frick:

I'd like to ask Ed a question since he's familiar with the sands in Michigan on our side of the State. We have had in the older, small residential wells the old, type two metal screens that are supposed to be subject to encrustation and dielectric action. These older wells also are of small diameter and have low pumping rates. We have put all stainless steel points in them which would have lower intake velocity, and we've had a great increase in the amount of encrustation on several of these wells. I wondered if you would have any calcium deposits, and encrustation, just cementing over of the screen. Some of the older screens have lasted for 10 to 15 years, but these new screens are completely cemented over in 2 years' time. I wonder if you would know anything about that.

Edward M. Burt:

Are you talking about replacing the screen? You've pulled the screen?

Jerry Frick:

Yes, we've pulled the old type out—of course they've been plugged up but they had been in for 10, 15, or 20 years. Then we put in the newer type, and maybe in 2 years' time they're encrusted.

Edward M. Burt:

When you make this change do you redevelop the well—acidize it, clean it up?

Jerry Frick:

Not acidizing the well—it's in the small 2-inch diameter. In the same area, we'll put in 4-inch wells which would have a lot more intake velocity, and we don't have trouble; it's just in the small diameter wells which have slow pumping rates.

Edward M. Burt:

My point was that if you simply pulled the screen and set a new one in its place and you haven't redeveloped, you haven't done anything about the plugging that is occurring in the formation outside of the screen.

Jerry Frick:

Well, in our area the formation all caves in when we pull the old screen out. We have to drive the new one or drill the hole out and install a new one; sometimes a formation may even have heaved up the pipe and we have to clean it out and install a new screen just as if a new well were being drilled. The only development that the small diameter wells get is only that which is incidental to their being pumped; and unless we have problems where there's low capacity, we sometimes surge them and develop them a little more. But not normally, no.

Edward M. Burt:

Well, then I'm afraid I can't answer your question.

Leslie G. McMillion:

We had some questions left over today regarding Jim Waltz's paper which he didn't have time to answer.

James P. Waltz:

One of the questions was, "could you put on a slide showing a rock formation and point out dips, joints, sets, etc. for those nongeologists who are not familiar with the jargon." Well, obviously over the microphone I can't put on a slide, but I might at least define what a joint is. If there are still any nongeologists, and for the record, the joint is a crack in the rock, a fracture in the general sense, along which no movement has occurred. A very interesting characteristic of joints is that they often occur in geometric patterns that are fairly predictable in their orientation. In other words there is seldom a single crack, there are usually a number of cracks that are parallel to one another, all of them oriented in approximately the same direction. And usually there is more than one set of these cracks. Secondary and tertiary sets of joints can usually be found and each of these has a characteristic direction and dip, at least characteristic in a statistical sense. Dip is simply the direction of inclination. The direction of dip defines the direction of inclination. The magnitude of dip is the angle from the horizontal, the vertical angle. So you can have a gentle dip or a steep dip, and the direction is the direction that water would run off if you were to pour water on one of these fracture surfaces. Strike is a term that is commonly found in the geologic literature. It isn't necessary to use the term strike. If you define the direction and magnitude of dip of a fracture you have completely defined its geometric characteristics.

A second question: "For the first study, was the degree or amount of pollution in the wells simply the amount of *E. coli* bacteria?" For most of the wells that we sampled in this mountain pollution study, we considered the well to be polluted if we were able to get several samples from the well which showed amounts of more than 1 *E. coli* per 100 ml sample. The health standards are consistent with this criteria—that if you find more than 1 per 100 ml, it's considered contaminated. If we were able to reproduce this result we considered the well to be contaminated. I considered the arrangement as sort of a black and white situation, either there are *E. coli* present or there are not, and it wasn't of much concern to me whether there were 2, because it's a matter of degree, like pregnancy and the common joke.

Russell E. Larson, ARS, USDA, St. Paul, Minnesota:

This afternoon you showed a slide of a cabin down in this flat, gravel plain, and you indicated that they had pollution problems. Did you say they corrected the problem by treating their well water, or treating the effluent that was getting into the stream, or did you say that the stuff just goes into the stream? What are they doing about this?

James P. Waltz:

To my knowledge, they are not really doing anything about it. Many of them are drinking contaminated water. A number of people who recognize the problem have chlorinators on their wells.

Russell E. Larson:

On their wells, yes. But, they don't worry about what happens to the effluent that is going out into the stream. Is that it?

James P. Waltz:

That's right. I don't know of any efforts by these people to treat the water before it leaves their leach-field system.

George Taylor:

I'm asking a question that should probably be answered by a sanitary engineer. I'm not a sanitary engineer; I'm a ground-water geologist. As I understand, they are using, more or less, one standard type of leaching field, septic tank design for most of these homesites. Is that correct? Is it pretty much a uniform design or is any consideration given to alternative designs that would be more effective in this kind of geologic terrain?

James P. Waltz:

Well, again, I'm groping a little bit as far as what all the alternatives are. I know there are different designs for leach fields, different types of distribution systems, drain tiles, and of course different sizes, depending on the amount of effluent that is anticipated. I firmly believe that there are perhaps better methods of designing these leach fields; primarily what I have in mind is that additional material could be brought in to serve as a filtering medium.

George Taylor:

Do you mean sand filters or something of that kind?

James P. Waltz:

Right–this sort of approach could certainly improve the situation.

George Taylor:

I would certainly think so, rather than relying on the natural material itself.

James P. Waltz:

There is an interesting battle going on in Colorado right now. There is a fellow who has developed an individual sewage disposal system that involves letting the effluent, still kind of ripe, go out on the surface of the ground, and as a matter of fact, I think this would be an improvement over the present situation because the small amount of soil that is present in the mountainous terrain would be defective as a filter and if the bacteria are brought in contact with the soil, with the surface, I think that many more of the bacteria would be removed than the present situation where they scrape away all of this good soil, the 6 inches, 8 inches, 1 foot or 2 feet, and then they put their leach field bed right on the bare rock. So there certainly are improvements in the design that could be applied right now.

Paul Goydan, Koppers Co., Inc., Pittsburgh, Pennsylvania:

Under present Colorado landfill practice, do you permit septic tank construction in gravel or alluvial deposits today?

James P. Waltz:

I assume that the answer is "yes." I am not directly involved in approval of septic tank locations. The county sanitarians are usually the agents who say, "Yes, you can put your septic tank here or your leach field here." I keep using the term septic tank when really we're talking about the leaching field that is the critical element. The septic tank functions fine because, in terms of releasing effluent, it does it just as well in the mountains as anywhere else; it's the leaching field end of the treatment that is failing, in my estimation, in the mountain. And, it fails where leach field effluent can pass into clean gravels because the gravels do not adequately filter and purify the effluent, and I have seen a number of instances where very clean gravels have comprised the "soil" into which these leach fields have been constructed. I had some argument at dinner this evening that some of the mountain streams, which I generalized about, have perhaps much tighter alluvial materials than I have admitted; and I think certainly there must be all kinds of conditions, because if you get very high in the mountain streams you begin to get into glacial materials or you have all sorts of permeability characteristics.

Paul Goydan:

In an alluvial type deposit where you essentially have flat terrain, and your distribution field is 2 to 3 feet below the surface, and in this very permeable material and no surface cover, you may expect a fairly aerobic type of condition to exist. Now would this perhaps enhance the over-all degradation, the ultimate goal of getting a fairly safe by-product? I'm curious because under ideal conditions where we do have the necessary soil depth and the necessary degree of degradation occurring we're in fine shape. But what happens in a very permeable type material?

James P. Waltz:

Let me comment first and I can be followed by Steve. As long as the effluent is passing through very permeable materials I question the amount of filtering and adsorption that can occur. I'm sure it's a matter of degree and that if you go far enough through highly permeable material you can achieve the same effect as passing the fluid through a few inches or a few feet of appropriate soil material. But this is really outside my area of expertise.

Steven N. Goldstein:

I'll try and place a little perspective on it. First of all, when you look at the soil system itself it's thought that most of the degradation is being accomplished by microorganisms, and so you must have the makings of a soil, some kind of an environment in which these organisms can live in number and sustain themselves. If you just have gravel I'm not sure that when effluent is not being applied the environment would be all that great to keep them alive. Now remember if you're talking about just gravel, they're going to swish right through there. It's not going to be a very long percolation. I was reading some minutes of a Symposium held up at Dartmouth in March of this year and I believe I'm quoting now from Professor Ryan Locke from Connecticut University. He came up with an interesting point, if indeed it's him that I'm quoting. He indicated that while clays perc much more poorly, much more slowly, much more impermeably than sands—and sands just seem to be great—it's really the clays that are doing—what's the jargon word—"beneficiation" to the water, actually purifying it a lot more.

Paul Goydan:

You mean adsorption?

Steven N. Goldstein:

Well, whatever it is that the soils do, clays are doing it better than sand; in other words, they're taking a lot more of the objectionable quantities out of the water by perking slower, and a lot of people say they don't want to put a leach field in clay. But, if you design a leach field of sufficient size to handle your load, clays apparently are treating the water a lot better than sands. And it may be because they give a better climate to the microorganisms.

Paul Goydan:

This perhaps gets a little bit into the ethics of the true purpose of the septic tank, or landfill or anything you are speaking about. Do we really want to absorb or adsorb, or whatever the term may be, onto something such as a clay or do we really want a degradation? I mean, are we just in fact perhaps storing this? I realize you desire permeability so that you may hold this particular material that is giving your substance BOD or COD so that microorganisms have sufficient time to act upon it. But this is not the same thing as physical adsorption and perhaps the distinction here should be made. The clay will adsorb perhaps, but unless it has the necessary biological population or organic matter in the vicinity to function, it will not really degrade. And perhaps this is really ultimately what we want. So that's why I asked the question. Perhaps we can still achieve the desired ultimate goal of degradation through a little more permeable type material, something almost like a trickling filter, although in trickling filters you do have algae and perhaps insects and this type of thing that helps the system along. But in a sense, maybe we can have an underground type of trickling filter and not adsorption as such.

Russell B. Stein, Ohio Division of Water, Columbus:

I came in here a little late and I wanted to inquire about the use of septic tanks. In Ohio, septic tanks in recent years have been under quite a bit of scrutiny and, as a matter of fact, I think that in some counties they are actually outlawing them on new installations. Now, of course, in established farms and things of this nature, if you have a septic tank you continue to use it. The reason for the scrutiny, I suppose, at least in our part of the country, is that in the glacial till soils and the high percentage of clay, septic tanks just simply do not work. We were talking about alternatives for individual waste disposal and I wanted to ask the question, has anybody discussed in this section the use of aerobic units, aerobic digesters or egg beaters, or whatever you want to call them? This is something which, in a few counties in Ohio, if you develop a housing development in a suburban area, you either have to go into this type of disposal or you have to go into a central sewage treatment plan. Our experience with a tight clay soil indicates aerobic units are a better means of sewage disposal for the individual homes. There are disadvantages, the main one being that people pull the plug on them and they just discharge raw sewage. But if there was some regulation on that, these would do a pretty fair job of aeration and sewage treatment.

Edward M. Burt:

Earlier we talked about the different types of sewage treatment and the discussion of septic tanks is like primary degree treatment which accomplished certain functions. You have perhaps heard of secondary degree treatment which takes this criteria of primary treatment to a higher degree of treatment. But I'd like to point out, both to you and to the other speaker, that when you're talking about septic tanks, you're really talking about the mechanisms involved in secondary degree sewage treatment plants; further, we should realize that the next step after that is tertiary level treatment which in the Midwest now consists of phosphate removal, but pretty soon it's going to include denitrification. Let's all bear in mind that when we talk about any one of these treatment methods, if we don't take a look at the total ecological picture we're just pushing the marble around. We say that *E. coli* in certain concentrations are indicative of pollution so we want to chlorinate and kill them down to an acceptable level. We do not like high biological oxidation demands (BOD); so, we satisfy the oxidation of bacteria to accomplish an acceptable degree of treatment. But the nutrients are still there but may be in another form. The reason Michigan is going to oxidation lagoons, aerobic ponds, and spray irrigation is to utilize—even use up—the nutrients, the effluent from a treating process, in irrigation of crops. Thus, the cropping is an important part of the treatment; for instance, phosphate is one that is readily picked up by many of your soil particles, especially your clays, by adsorption. The growing crop can again pick that phosphate up and utilize it and so you are completing the cycle of changing it around. In like manner, the crops use nitrates in their growth cycle.

Russell B. Stein:

I think you misunderstood me or I got off the track. I was referring primarily to individual home sewage treatment. Whatever method you choose for sewage disposal, of course depends on individual conditions, but I've seen, particularly in Ohio, so many cases where people have a septic tank system with as many as four leaching tile fields on a half-acre lot. Their whole yard is a leaching tile field yet in the spring of the year they have raw sewage coming up through their grass.

Edward M. Burt:

They don't have raw sewage, they have primarily treated sewage, which isn't acceptable.

Russell B. Stein:

I don't know what it is, but it's pretty raunchy stuff. It's black and evil smelling.

Steven N. Goldstein:

There are individual system aerobic treatment units which in many ways are similar to the septic tank in construction except that air is mechanically pumped into the tanks, thus attempting to keep the conditions aerobic rather than anaerobic; a septic tank is anaerobic digestion, so now you have aerobic organisms taking over and it's more than just bacteria. You may have other kinds of bugs involved there. It's still not entirely clear; however, a lot of investigations show consistently better performance for properly operated aerobic units as opposed to septic tanks. There is only one hooker. The hooker is you have to keep that pump working. If the pump doesn't work then the whole thing goes "kaput." And that turns the individual homeowner into a waste treatment system operator; he must check on the pump, he must make sure everything works properly and this is something which in general he doesn't want to do nor does he know how to do it. Secondly, there are very few qualified people who can maintain the system even when the homeowner finds out that something is going amiss. In general, some places that do require that you have aerobic systems as opposed to septic systems also require that you have a maintenance contract with a qualified maintenance person. So it does show some promise but there are a lot of problems in terms of proper maintenance which you never have with a septic tank.

James P. Waltz:

One quick comment regarding your situation in Ohio. As I understand the aeration system, you still have the effluent to get rid of, so you haven't solved anything other than making the fluid more acceptable by switching to the package aeration unit.

Russell B. Stein:

This is true, and then it's simply a matter of the fluid either going into a leaching field or more frequently into an open ditch or the nearest water course. The comment I started to make, and as this gentleman just emphasized, is the fact that some people don't want to spend the money for the power to operate another motor; and, they do pull the plug on these things. So, if you're discharging into the low part of your land, then you're strictly discharging raw sewage. If you had some control that prevented this from being done these might perform satisfactorily. I'm sure it's a legal problem, and it's certainly a moral problem. But if they maintain them, it's my feeling that in certain geologic conditions it's a much better sewage disposal system because the effluent is of a much higher quality.

Edward M. Burt:

We seem to be evolving around anaerobic sewage treatment and aerobic sewage treatment. Your septic tank is anaerobic and all your anaerobic systems characteristically are the odoriferous ones. The aerobic ones are not so odoriferous. Even if you had an aerated septic tank system and then went back into the soil with a leaching tile field, the nutrients are right there, the anaerobic bacteria in the soil would take over and you would be right back to your anaerobic thing that came out of the septic tank in the first place. It would just change the type of bugs that thrive on it, back to the smelly mess.

Roy E. Williams, University of Idaho, Moscow:

Mr. Burt, what happens to a State or federal agency which issues a permit to dispose, and which disposal results in a gross pollution problem such as the one you were discussing today?

Edward M. Burt:

Under the permit system of Michigan, the Michigan Water Resources Commission has jurisdiction over all of the surface and ground waters of the State. This agency's permits are not fixed in time. In other words, each one is a contract with either a public or private corporation that says "O.K., you want to do this, these are the limits, this is the degree of treatment that you have to accomplish; this surface or ground water is acceptable for receiving this type of waste." The party receiving the permit has to monitor the waste discharge and has to submit reports and proofs monthly that it is living within its stipulated range. I mentioned this afternoon that there is a "hooker" clause at the bottom of all these contracts which states that at such time that a higher degree of treatment or a nuisance or any other thing is involved that requires re-evaluation and re-establishment, the State agency can order a change.

Roy E. Williams:

In other words, nothing happens to the State agency if pollution results? Is that correct?

Edward M. Burt:

Yes, the responsibility rests on the user of the resource.

Paul Goydan:

Mr. Burt, if you only have the funds to construct a few monitoring wells, where would you put them, and to what depth below the water table to learn the vertical extent of contamination?

Edward M. Burt:

We design the monitoring wells after we have drilled exploration wells to evaluate the geologic and hydrologic conditions, and to establish the observation well pattern. To illustrate this with the example which I discussed this afternoon, we first found out the basic conditions, the direction of flow, area of contamination; and we worked from the surface of the water table on down. In other words, we sampled as we went down. From this we came up with a final design of the monitoring system with shallow wells that were in the upper 15 feet of the water table, and others within the bottom 15 feet. (This was a water table aquifer, incidentally.) But, the business of limited funds goes back to the responsibility of having sufficient proofs that you are complying, or you have sufficient data and it doesn't stick. It's the responsibility of the party that's going to use this resource to protect it. And if he does cause contamination or pollution, that is unacceptable and he has to correct it. As far as the regulatory agency is concerned, they don't care what it costs.

Russell B. Stein:

Mr. Schmidt, we had a relatively small nitrate contamination problem in a rural area of Ohio which I worked on a number of years ago. It only involved about 4 or 5 square miles and possibly 25 or 30 individual farms, but we had some pretty high nitrate values. We had a situation similar to what you described in Fresno where there were several potential sources of nitrate in the water. For example, there were agricultural fertilizer, septic tanks and feedlot operations. In our chemical analyses we tried to make a distinction between some of these sources by analyzing for chloride and also potassium. We had pretty good base data in this area and we knew what was normal for most of these values; and, in some instances where we had rather high nitrates, we would get high potassium values and low chlorides. In these cases we suspected chemical fertilizers. In other instances we had very low potassium (maybe zero potassium), high nitrate, and high chloride and this led us toward sewage sources. Did you do any analysis with potassium and do you think this is a valid tool to use in this kind of study?

Kenneth D. Schmidt:

In my study area there is one outstanding source of potassium, namely winery waste water. One of the by-products of the winery operation is potassium bitartrate. So, using potassium would be logical near wineries. The problem with potassium is that it is not very mobile in these alluvial groundwater systems. Potassium is also high in sewage effluent as compared to most ground water. If one wants to distinguish between agricultural fertilizers and other sources, chloride is a very good constituent to consider. There are difficulties in using potassium in agricultural areas such as in Fresno County. Little potassium fertilizer is used as compared to anhydrous ammonia. Anhydrous ammonia when applied to the soil is known to have a great replacing power. Thus, cations such as calcium, sodium, and potassium may be replaced by ammonium ions from the fertilizer. However, in areas other than alluvial basins, potassium may be a useful cation. People should be encouraged to use all available chemical data, not only chloride and potassium, but boron, fluoride, and other constituents.

Russell B. Stein:

I probably should have clarified this a little better. This was an area in northwest Ohio which was in a very shallow carbonate area; the highly cavernous limestone aquifer was exposed at the surface in the area; it was likewise an area of extremely poor well construction. Most of the wells were between 50 and 75 feet deep but were only cased to depths of 10 feet or less and for this reason we felt we were getting extremely rapid drainage from the surface directly into some of these wells. We corrected most of the nitrate-contaminated wells by deepening them and double casing them, to 100 feet or so, and it did solve the problem. Now, concerning the potassium, we have observed that if ground water in Ohio has more than 1 ppm or maybe 2 ppm something unusual is happening; thus, we were alarmed because we were getting 20 to 30 ppm in some of these wells. Something caused this and in this instance it wasn't due to wineries.

Paul Goydan:

From hearing the talks and discussions the last 2 days, it seems to me that we're largely talking about the soil as a means of disposal, not only in landfills or in septic tanks; but irrigation has also been mentioned. I would like to emphasize this. Much of the research today has been directed towards surface-type treatments, and we have really neglected this natural resource we have in the soil and its ability to do an effective job. One of the things that should come out of this conference is to direct research and funds to this area. I believe this has a lot of promise. We're not only talking about contamination, we're talking about disposal, degradation, and available means for solving our problems. Let's look more closely at the soil, and one area I'm particularly interested in is soil irrigation. We haven't had too much discussion there but this is an area I'd like to see the various control officials, industry, and organizations get involved in. Perhaps we shouldn't be so ignorant when it comes to subsurface means to dispose of our waste. Let's get down to the nitty gritty, face the facts, and really try to solve the problems; and hopefully this will be something that will come out of the conference.

Edward M. Burt:

I agree with you. I'd like to point out a couple of studies that are going on. One that has many years of background research is at Penn State University. We are participating in an EPA financed study. The City of Belding, Michigan, with a population of around 5,000 has a series of waste water lagoons. A portion of this effluent is being used in two irrigation areas, summer irrigation and winter irrigation. This is all layed out for 2, 3, and 4 inches of application, the type of soils, and it's a complete type of study where you analyze the soil, how much penetration, and effect on various crops. In addition to these 2, something about the sewage treatment operation known as the Muskegon County project—this is also in Michigan. There again they are talking about oxidation ponds, lagoons and irrigation, and some questions were raised today about this. There was comment that under the irrigation area they were speaking of underdraining it with tiles; I do not know the details but my understanding is that while this is another sandy lake plain with unconsolidated sands, it will run down to maybe 50 or 75 feet and their intention is to ring the irrigation fields with dewatering wells and pump (in the terminology of Penn State) the renovated waters captured by these wells that are intended to collect anything that seeps through and isn't used up in the soil or taken off by the vegetation, and discharging that to a surface water body.

Paul Goydan:

We do need to look at the specific variables involved. It is fairly well established that it is feasible and practical in many instances to treat waste fluids, particularly municipal sewage, by spray irrigation and production of vegetative crops with it. The Penn State studies in particular showed these systems to be feasible. But, these studies fail to get down to what the real mechanisms involved are, and to show how the data can be extended to and used in other areas. They showed some of the characteristics of their system and they showed that the system can work, and they were working with a domestic waste at that. But, when you start talking about industrial waste and various specialized types of chemistry, here again is another story. I think we are moving in this direction and I'll be looking forward to getting the data and the results.

Leslie G. McMillion:

Along this line of using the soil as a living filter and treating media for sewage and waste waters, I have recently become convinced that such waste treatment methods could have a place in the over-all plan for sewage treatment and disposal in such heavily populated areas as Long Island, New York. If you're familiar with the ground-water situation on Long Island you realize that past and present methods of handling the Island's municipal and domestic sewage have resulted in some publicized cases of ground-water contamination. These cases involve local buildup of relatively high concentrations of nitrates and other substances such as chlorides. The apparent cause of the local problems is downward seepage of contaminating fluids from septic tanks, sewage lagoons, and the like. There are literally thousands of individual domestic sewage disposal systems on the Island since most of it is not served by public sewer lines.

The soil treatment method could be especially useful on Long Island since a principal nutrient source which can be removed by this process is nitrates; and, as you probably know, contamination by high levels of nitrates is one of the primary concerns of the Long Island situation. However, we cannot disregard the difficulties that could be involved in instituting the actual treatment operations in such areas as this one; the main problem could be the availability and price of land for the operation. Another difficulty could be technical know-how itself; and in this regard, we are thinking of the actual design and operation of a unit.

While these concepts of soil treatment of wastes are in their infancy, it is interesting to note that they are not being totally ignored in the country. A considerable amount of money has been released to the U. S. Army Corps of Engineers so that the agency can make studies of waste water collection, treatment, and disposal in 5 of our large metropolitan areas: San Francisco, Chicago, Detroit, Cleveland-Akron, and Boston. It is my understanding that what prompted the initiation of these studies was concern over the possibilities for using the so-called "land treatment" methods (such as spray irrigation of waste water) as a way of treating municipal sewage. While many are skeptical about these methods providing all the answers, we do see a place for them in the total waste treatment and disposal picture. It may be inconceivable that all the waste fluids from these 5 metropolitan areas could be treated by the land treatment approach; but it is reasonable to assume that some of it could be treated in that fashion. So, there may be possibilities for broad applications of this concept. If possibilities exist for its application in the northern areas of the nation, the opportunities for success of the method should be much greater in the southern and southwestern States where the growing season is longer.

Edward M. Burt:

In the conversations we've had in the last 2 days, while the emphasis is on utilizing the soil for waste treatment and what happens from the landfill and from the sanitary waste water aspects, and industrial aspects, another thing that has been paramount is the general realization that it takes the combination of many types of skills to accomplish a workable solution to these problems. It isn't just the geologist or the hydrogeologist or the sanitary engineer. When you start working with the soil you should be looking for the agricultural specialist because the type of crop that you utilize in an irrigation system can make a great deal of difference. For instance, the crops that we're most frequently talking about in Michigan are corn, because it has a very good extractive characteristic; Reed canarygrass; and brome-alfalfa mix. Now some types of alfalfa instead of taking nitrogen out of the soil, take it out of the air and put it in the soil. We're looking for those things that take the nutrients back out because to a degree the soil is a storage reservoir for those things that you want captured by adsorption and then taken back out. Clay minerals have generally very good capability for removing phosphates, but you want to get it back out of there; otherwise you're storing it.

This brings up another thought—I mentioned today that this industrial company in the final treatment methods that were used, the highly concentrated combustible waste which was in the order of 1½ to 2% went to incineration, and the question was asked, "What happens to the waste from the incineration?" This is collected and goes along with the other 2½% of the wastes that require additional treatment, into a concrete stabilization lagoon or pond with aeration, for removal of ammonia (for instance), and where we are trying to develop a growth of bacteria to prove the feasibility of going into a standard secondary degree treatment process. I mentioned that the cost of incineration was about the same as the cost of disposing of the same volume via a deep disposal well; thus, some of you are perhaps wondering why we didn't go to deep subsurface disposal. I mentioned we'd been considering casing to a depth of about 3,000 feet and disposing into formations between 3,000 and 5,000 feet. I, as a geologist, worked on the design and the method of deep well disposal and one of our sanitary engineers, along with some combustion engineers, studied the economics of the incineration; then we sat down and argued the pros and cons of each method. In those discussions, I expressed a personal philosophy that I still adhere to—that the more things we can handle on the surface of the earth where we can readily get at the mechanical workings to make proper repairs, the better off we are in the long run.

Leslie G. McMillion:

I have been notified that all three of the other sessions have adjourned. In light of that and since it is past ten o'clock, we will very shortly conclude this session.

It is most difficult for me, as session chairman, to appropriately express my appreciation for such tremendous participation as we have had here tonight. I thought that our panel really outdid themselves in answering the questions from the floor and providing other comments for the record and for our edification; I thank each one of you for your excellent contribution. This session would not have been possible without the presence and active participation of you who have attended tonight. We thank you for your attendance and your enthusiastic participation. We were very glad that several of you helped answer some of the questions that were asked, and provided information on some knotty technical topics.

This session has been especially interesting and stimulating. I am sure that we all hope that the enthusiasm of this meeting will carry far beyond Denver and this point in time.

A Systems Approach to Management of the Hanford Ground-Water Basin[a]

by D. B. Cearlock[b]

ABSTRACT

Mathematical models for simulating ground water and radionuclide movement as a function of time and space are being developed. In addition to the models, a man-machine interactive computer system is under development for use in model applications. In total, the research and development program will produce a management and engineering tool for use in analysis, decisions and policy formulations relative to management of ground-water systems.

The system is separated into sequential or parallel components that can be modeled independently of each other. This results in maximum capability to simulate all combinations of situations that may be encountered and in case of modifying or refining the models independently without having to reformulate the entire system. The system is composed of three major categories of models: (1) data models; (2) hydraulic models; and (3) water quality (transport) models. Data models calculate input characteristics required for operation of the hydraulic and water quality models from a minimum of field measurements. The Transmissivity Iterative Routine for calculating transmissivity distributions and the Sorption Transmissivity Routine for calculating sorption coefficient distributions are two types of data models. The hydraulic models predict the flow of ground water in saturated and unsaturated soils. The Partially-Saturated Transient Model, which describes unsaturated, transient flow, and the Variable Thickness Transient Model, which describes saturated, transient flow, are included in this category. The water quality models predict the movement of the waste through the subsurface soils. The Macro-ion Transport Model, which describes macro-ion movement, and the Micro-ion Transport Model, which describes micro-ion movement, are included in this category. The assumptions used in developing the system of models, justification of these assumptions, the interrelationship of each of the models, and the intended application of the entire system are presented.

The man-machine interactive computer system provides an efficient means for the engineer to interact in the problem solving functions using the previously discussed models. The system allows the engineer to rapidly scan a large number of alternatives and use his experience in rapidly converging on a solution. The components of the computer system and their functions are described. Examples showing how the computer system is being used with models that have been developed are presented.

INTRODUCTION

Since the beginning of the Atomic Energy Commission Hanford Project in the mid 1940's, geological and hydrological investigations have been conducted to establish and evaluate management alternatives with respect to storage and disposal of waste materials in the vadose zone above the regional water table. Initially these investigations consisted mainly of analyzing (1) well logs and driller's samples for stratigraphic information and, (2) ground-water potentials for ground-water movement patterns and rates. The efforts concentrated on defining and understanding the water-table aquifer because of its direct relationship to waste management activities. Historically, Hanford waste management practices have been based on conservative assumptions and an extensive monitoring program to evaluate and measure the effects of these practices.

Investigations have continued in an effort to improve the understanding of the water-table aquifer. The aquifer has been classified into textural types and pump tests have been conducted to determine the permeabilities of each textural type. This data showed that the Hanford ground-water system was highly variable.

In an attempt to develop a practical tool for managing the ground-water basin, simulation techniques were employed. Initially, simple graphical flow net analysis and analog models were tried. With the increase of capability and flexibility of the digital computer, the emphasis shifted to mathematical simulations. The modeling effort was directed toward simulating steady, ground-water flow. These models were theoretically sound, but the output was less reliable than desired because the data input requirements could not be economically satisfied. It was, therefore, necessary to make compromising assumptions in order to use the models. In addition, the models could not simulate transient conditions or waste transport, which are required to answer many of the pertinent problems associated with management of a ground-water basin.

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Recent pressures for multiple uses have posed important questions concerning the management of the Hanford ground-water basin. Although significant time and effort have been expended on collecting field data and conducting field investigations, methods have not been available to utilize these data to produce the answers required for waste management decisions.

To provide the methods for answering questions concerning management of complex ground-water basins, a major program was undertaken to develop a system of mathematical models for simulating ground water and waste movement as a function of time and space. Selection and development of the system of models was based on the economics of data input requirements, precision of results required, and the practicality of application. In addition to the models, a man-machine interactive computer system is being developed to provide an efficient means for utilizing the models and analyzing the results. In summary, the program is producing a management and engineering tool for use in analysis, decisions and policy formulations relative to management of ground-water systems. A brief description of the models, assumptions and justifications of the assumptions, the interrelationship of each of the models and the intended application of the entire system are presented. Also included is a description of the interactive computer display system.

DESCRIPTION OF SYSTEM COMPONENTS

The objective of this program is to develop a ground-water resources management tool which can be applied practically to both local and regional ground-water systems and which will provide reliable answers to those pressing problems associated with the exploitation of ground-water systems. To accomplish this objective, the ground-water system was separated into sequential and/or parallel components that could be modeled independently of each other: saturated flow, unsaturated flow, and contaminant transport. This resulted in: (1) maximum capability to simulate all combinations of situations that could possibly be encountered, (2) generally applicable models that could be applied to any ground-water system in which the basic assumptions were satisfied or where the assumptions were not compromising, and (3) ease of modifying or refining the models independently without having to reformulate the entire system.

The model development effort is presently separated into three major categories of models: data models, hydraulic models, and water quality (transport) models. Data models calculate, from a minimum number of field measurements, input characteristics required for operation of the hydraulic and water quality models. The hydraulic models predict the ground-water velocities or rate of ground-water movement in the unsaturated and saturated sediments. The water quality model combines the ground-water movement calculated by the hydraulic models with soil-waste reactions that contaminants would undergo during a traverse through the soil to predict the contaminant movement. In effect, the ground water is a transporting mechanism and can be simulated independently of waste movement. A simplified schematic showing the interrelationships between the data, hydraulic and transport models is shown in Figure 1. Table 1 lists the models and their respective functions as well as input data requirements and output information. Each of these categories will be discussed in the following narrative.

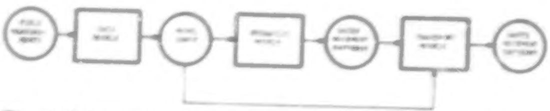


Fig. 1. Schematic diagram showing interrelationships and data flow between the various categories of ground-water models.

Data Models

Data models include those developed to calculate (from a minimum number of field measurements) input characteristics required for the operation of the hydraulic and water quality models. In the initial planning stages of the program, it was realized that it was not economical to obtain input characteristic data using the classical method of extensive field data collection programs. Therefore, models were developed which would use data that were available or could be obtained economically, and from these, calculate the desired model input. The most important model that comes under this category is the Transmissivity Iterative Routine.

It is common in ground-water systems for permeabilities to vary considerably over study areas; thus, the assumption of a homogeneous permeability distribution will usually result in erroneous predictions in changes in ground-water elevations and flow patterns. Because of these variations in permeabilities, the cost of establishing

Table 1. List of Ground-Water Models, Functions, Input Data Requirements and Outputs

Models	*Function*	*Input*	*Output*
Data Models:	Calculation of model input from minimum number of field measurements.		
Transmissivity Iterative Routine	Calculates transmissivity distributions.	1. Ground-water potentials; 2. Transmissivity measurements.	Heterogeneous transmissivity.
Hydraulic Characteristics Routine	Calculates permeability function (permeability vs. capillary pressure relationship).	1. Desorption curve (moisture content vs. capillary pressure); 2. Saturated permeability.	Permeability function.
Sorption Transmissivity Routine	Calculates sorption coefficient distribution.	1. Sorption-transmissivity relationship; 2. Transmissivity distribution.	Sorption coefficient distribution.
Micro Sorption Routine	Determines the coefficients for the Kd-macro-ion relationship.	1. Experimental data for specific soils and wastes.	Coefficients for the Kd-macro-ion relationship.
Hydraulic Models:	Simulation of subsurface water movement.		
Partially-Saturated Transient (PST) Flow Model	Simulation of unsaturated flow.	1. Hydraulic characteristics; 2. Boundary conditions; 3. Initial conditions.	Time-dependent ground water: (1) potentials; (2) velocities; (3) flow rates; (4) flow paths; and (5) travel times.
Variable Thickness Transient (VTT) Flow Model	Simulation of saturated flow (approximates three-dimensional systems).	1. Transmissivity distribution; 2. Initial conditions; 3. Boundary conditions: includes quantities and location of recharge calculated by the PST Model.	Time-dependent ground water: (1) potentials; (2) velocities; (3) flow paths; (4) flow rates and (5) travel times.
Transport Models:	Simulation of subsurface waste movement.		
Macro-ion Transport Model	Simulates macro-ion movement in saturated and unsaturated soils.	1. Cation exchange capacities; 2. Initial concentrations on the soils; 3. Ground-water velocities from either PST or VTT models; 4. Boundary conditions.	Macro-ion concentrations in liquid and solid phases as a function of time and space.
Micro-ion Transport Model	Simulation of micro-ion (trace) movement in saturated and unsaturated soils.	1. Sorption coefficient distribution;* 2. Initial concentrations on the soils; 3. Macro-ion concentrations as a function of time and space from the macro-ion model; 4. Ground-water velocities from either PST or VTT models; 5. Boundary conditions.	Micro-ion concentrations in liquid and solid phases as a function of time and space.

* Input requirements vary depending on the situation being modeled; i.e., either unsaturated or saturated and the importance of the macro-ion influence on micro-ion movement, etc.

an observation well network and making the many measurements required to assure a reliability permeability distribution quickly becomes prohibitive. To avoid the prohibitive cost of a massive number of field measurements, a computer routine was developed which allows calculation of the permeability distribution over study areas using a minimum number of field observations. The method developed, based on continuity of flow in a streamtube for a quasi-steady state ground-water system, utilizes the measured energy dissipation in a streamtube to calculate transmissivity and/or permeability at any point within the tube.

The program was written for two-dimensional systems where the transmissivity is assumed equal to the product of the depth and the average permeability over the vertical section of the aquifer. Although the method could be extended to include the third dimension, the field data available or that which could be obtained economically does not warrant such an extension at this time. Figure 2 shows the calculated transmissivity distribution for the Hanford Reservation ground-water system.

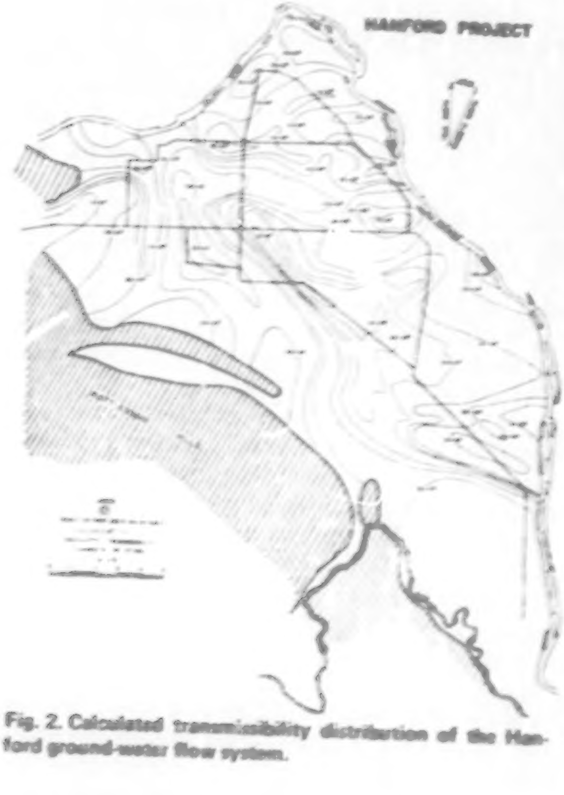


Fig. 2. Calculated transmissibility distribution of the Hanford ground-water flow system.

Using this transmissivity distribution along with the ground-water potentials, the existing travel times and flow rates from any site on the Hanford Reservation can be calculated. Figure 3 shows the relative travel time from a reference line located on a 50 square mile block of the Hanford ground-water system. The predicted three-pronged effect, a result of high permeability channels, agrees very well with measured observations of ground-water contamination in that area. The effects of heterogeneity on waste movement are explicitly shown by this three-pronged front. It would be impossible to simulate waste movement accurately in the Hanford system by assuming a homogeneous transmissivity distribution and using a large dispersion factor to mask the effects of heterogeneity. This is why it is necessary to have an accurate transmissivity distribution and why considerable effort has been expended in developing methods with which these data can be obtained economically. The photograph in Figure 3 was taken off a computer generated Cathode Ray Tube (CRT) display.

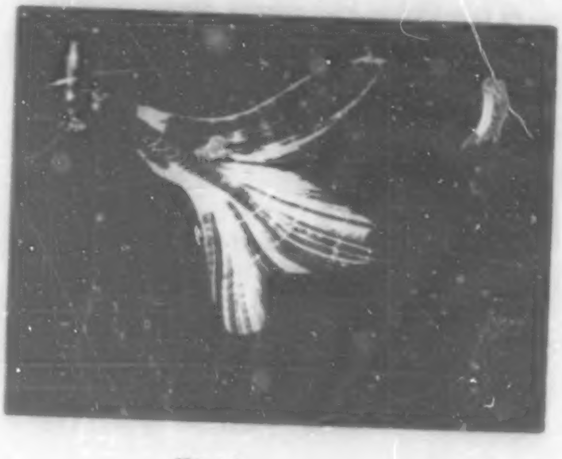


Fig. 3. Ground-water movement pattern at time = t_1 originating from a reference line on a portion of the Hanford ground-water system.

This program is presently being extended to include transient systems. In addition, it has been adapted to a man-machine interactive computer system (which is discussed later) so that the errors in interpreting ground-water potentials can be minimized. This involves an iterative process of reinterpreting ground-water contours from the original data and recalculating the transmissivity distribution. The process would be impractical using standard computer input/output procedures. The method is called the Transmissivity Iterative Routine.

In modeling unsaturated flow, it is necessary to have a mathematical description of the hydraulic characteristics of unsaturated soils. The hydraulic characteristics consist of two relationships: (1)

permeability versus capillary pressure (permeability function); and (2) moisture content versus capillary pressure (desorption curve). Obtaining the permeability function from laboratory measurements is extremely time consuming and expensive relative to the number of measurements required to accurately define a system. Methods developed for calculating the permeability funcrion from the desorption curve and the saturated permeability have been modified and used successfully. Since the desorption curve and saturated permeability data can be obtained without too much difficulty, this approach to establishing hydraulic characteristics of unsaturated soils represents a considerable savings in time and money.

The micro-ion (radionuclide) sorption coefficient is a function of both the soil type and the macro-ion concentrations. The Micro Sorption Routine determines the coefficient for the relationship between the Kd and macro-ion concentrations using a two factorial design regression technique. Experimental data must be collected for each soil type and range of wastes encountered.

On large systems, such as Hanford which covers in excess of 400 square miles, it is impractical to mount the field data collection program necessary to accurately define the spatial sorption coefficient (Kd) distribution. Therefore, a data model is being developed to calculate the Kd distribution for large ground-water systems utilizing a minimum number of field measurements. The approach being used is to relate the Kd to the soil type through the permeability/transmissivity distribution. Since an accurate transmissivity distribution can be obtained using the Transmissivity Iterative Routine, a Kd distribution can then be calculated from these data. Preliminary results are very encouraging. To use the method, available soil samples are analyzed to obtain the permeability versus Kd relationship. Once this relationship is established, the Kd distribution can then be calculated from the transmissivity distribution.

Hydraulic Models

It was decided at the initiation of this program that the most practical approach to modeling ground-water flow was to consider the unsaturated and saturated ground-water flow system separately rather than as a combined system. This decision was made in consideration of the field data available and the cost of obtaining additional data, the size of core memory in large computers presently available, and the computational time associated with use of large grid networks to obtain numerical solutions. Considering the systems separately results in having to define the hydraulic characteristics only at sites where unsaturated flow is important (points of recharge or injection). This limits the amount of data required on unsaturated soils and for most problems is not compromising. It is anticipated that the unsaturated model will be used to calculate the quantity of flow entering the ground-water system. The calculated inflow is then input to the saturated model to predict the changes in the ground-water surface elevations.

The capillary conductivity approach was chosen for modeling the unsaturated portion of the ground-water system. The model is based on continuity of flow into and out of an elemental volume where the permeability, hydraulic potential and moisture content are all a function of capillary pressure. The model is valid for transient, heterogeneous, saturated and unsaturated flow. The primary input requirements to this model are the hydraulic characteristics, permeability - capillary pressure, and moisture content-capillary pressure relationships.

The PST computer program will presently work in one and two dimensions, and in three dimensions for axisymmetrical problems. The program can be extended to include the third dimension. It should be noted that while the PST Model is used to describe combined saturated and unsaturated transient flow above regional water tables, it also can be used to solve combined saturated and unsaturated flow problems which include the regional ground-water system. The reason the PST Model is not used in this manner is that a model which approximates three-dimensional saturated flow (VTT Model), has also been developed. As mentioned earlier, using the two models significantly reduces the amount of input data and computer core memory required, as opposed to the entire system being modeled with the PST Model.

The PST Model has been used to simulate hypothetical buried tank and pipeline ruptures. Figure 4 shows output from two hypothetical problems that were analyzed with the PST Model. Figure 4(a) shows the moisture pattern developed at 223 minutes after a simulated pipeline rupture. The degree of saturation in these Figures is proportional to the intensity of light on the computer driven CRT from which the photos were taken. Therefore, white indicates saturation while black indicates the initial soil moisture. The various shades of gray indicate gradation of moisture between these two limits.

Figure 4(b) shows the moisture pattern developed at 16.55 hours after a simulated storage tank rupture. There are five geologically distinct strata which are represented by the four horizontal,

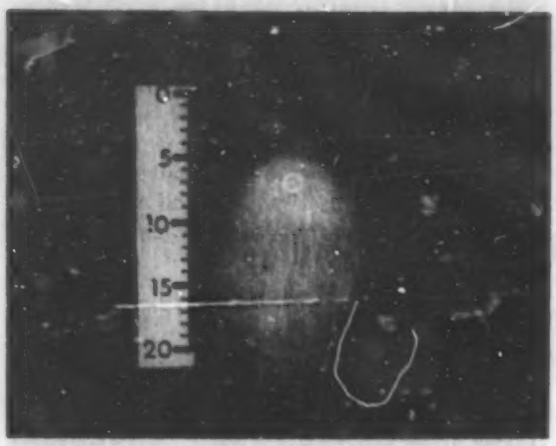


Fig. 4(a). Moisture distribution for a 3 inch pipeline break simulation (time is indicated from start of problem, and seal is in feet).

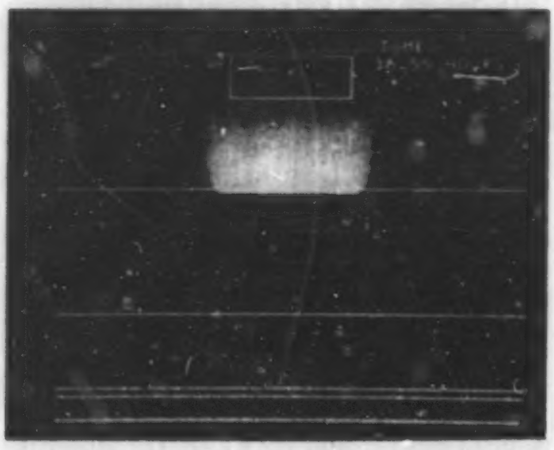


Fig. 4(b). Moisture distribution resulting from a simulated storage tank rupture.

Fig. 4. Computer generated displays showing output from the PST Model for two hypothetical problems that were analyzed.

white lines. The total distance between the tank bottom and the water-table surface is approximately 230 feet. Results from this model are encouraging since very little has been published relative to the numerical solution of the equation involved. The numerical problems encountered on the tank and pipeline break simulations were severe because of the low initial saturation (approximately 8% moisture content), the high positive heads and the large variations in permeabilities.

Studies of this nature are continuing in both field applications and for model verification. Model verification includes simulation of both one and two-dimensional columns under precise laboratory control utilizing nondestructive testing procedures. As a result of the testing to date, it appears that the model can be used to simulate any situation that will be encountered on the Hanford Reservation. The above simulations demonstrate the utility of the models in developing management policies and evaluating management alternatives.

For the saturated portion of the flow system. a two-dimensional model that approximates three-dimensional saturated, transient flow was developed. The model (VTT) was developed for a heterogeneous system where the permeability, aquifer bottom elevation, and storage coefficients are a function of space coordinates, x and y. Changes in transmissivities resulting from changes in water table elevations are factored into the model.

Comparative figures are presented to provide a quantitative understanding of the advances which have been made in simulating saturated flow since the inception of this program. Figure 5 shows the measured Hanford ground-water potential distribution compared with the potential distribution predicted by the VTT Model using a homogeneous permeability distribution and the Hanford ground-water system boundary conditions. As can be seen, the match in potentials is poor over much of the Reservation. In addition, waste movement calculated from such a potential distribution would be highly inaccurate relative to spatial locations and concentrations since the calculated flow paths and travel times would compare poorly to actual values. The assumption of a homogeneous permeability distribution has been used in many areas because of the lack of methods for economically obtaining a representative distribution. This assumption has also been considered for past models of the Hanford ground-water system. However, since an accurate knowledge of the direction and rate of the ground-water movement is a prerequisite to accurately predicting waste movements, a more representative distribution is necessary.

Figure 6 shows the same base map as in Figure 5 with the VTT Model output superimposed. In this case a highly variable transmissivity distribution calculated from the streamtube program was used (see Figure 2). As can be seen, the match of ground-water elevations and the shape of the ground-water contours is very good. The resulting prediction of waste movement would be considerably more accurate than in the first example and represents a significant step toward obtaining the objectives of this development program. The effect of grid size and other variables on the match is

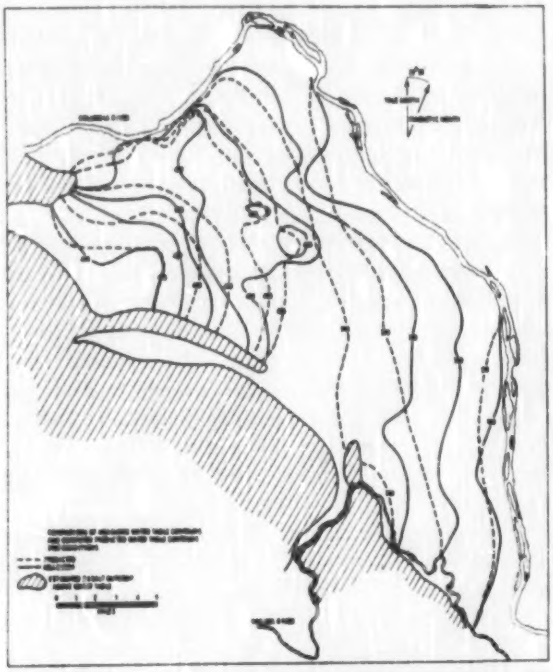


Fig. 5. Measured and calculated Hanford ground-water contours—homogeneous permeability.

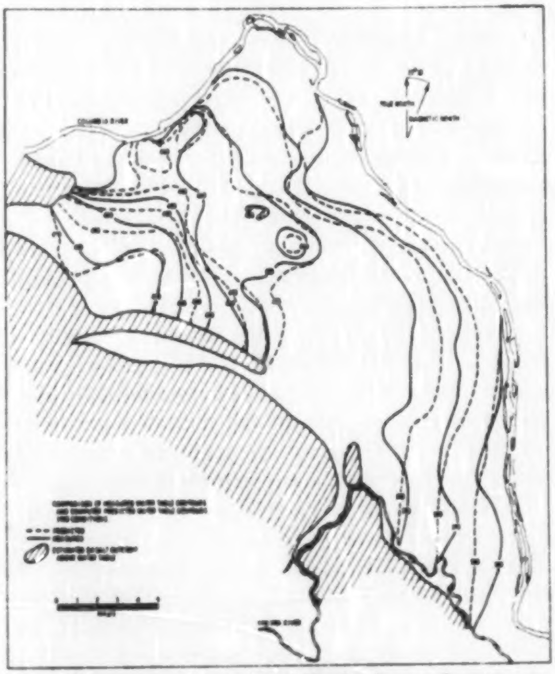
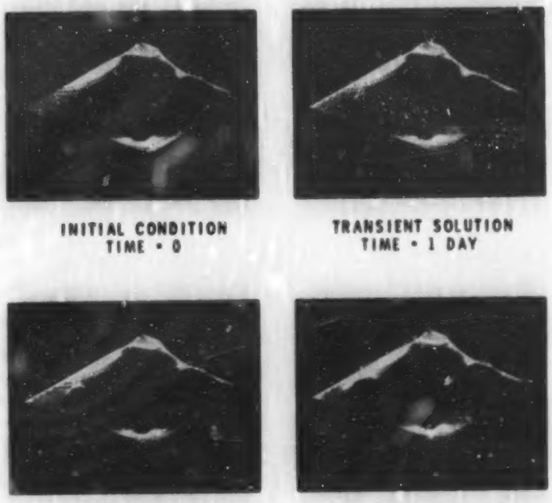


Fig. 6. Measured and calculated Hanford ground-water contours—calculated transmissivity.

under investigation. It is planned to use the Transmissivity Iterative Routine along with additional transmissivity measurements that have been made to further improve the calculated transmissivity distribution. With the new distribution, an even better match than that shown in Figure 6 is expected.

Output from the VTT Model used on an idealized test case is graphically shown in Figure 7. The solution shows the computer generated transient development of a mound that would result from discharge to a ground-water system.



INITIAL CONDITION
TIME • 0

TRANSIENT SOLUTION
TIME • 1 DAY

TRANSIENT SOLUTION
TIME • 3 DAYS

TRANSIENT SOLUTION
TIME • 13 DAYS

Fig. 7. Progressive change in ground-water surface resulting from discharge of wastewater to the ground.

Water Quality Models

Development of methods for predicting contaminant movement is based on the transport equation which incorporates fluid movement and contaminant reaction components into one interrelated equation. The transport equation is the analytical tool with which the time-dependent, concentration distribution of contaminants in saturated and unsaturated soils can be predicted. In the case of the nuclear industry, radionuclides of interest generally occur in trace concentrations relative to naturally occurring cations. By definition, trace ion sorption of a specific ion is independent of other trace ion concentrations. The trace ion movement is influenced, however, by the macro-ions in the system. Therefore, two transport models have been developed—one for describing the transient movement of the macro-ions, and the other for describing the transient movement of the trace (micro) ions. Both models are valid in saturated and unsaturated systems. The models take into consideration the *influences of convective ground-water movement*, hydrodynamic dispersion, molecular dispersion, sorption and decay. For the sorption reaction used, it is assumed that equilibrium conditions between ions in liquid and solid phases exist.

Satisfactory numerical solutions to the convective transport equation cannot be obtained using standard techniques such as those used in the hydraulic models. The method of characteristics was used to obtain a two-dimensional numerical solution. Both models are currently working and are undergoing further testings and refinement.

The input data required for the water quality models are the ground-water velocities (obtained from the hydraulic models), the dispersion and diffusion coefficients (which can be obtained from laboratory and field tests) and the sorption coefficient. Other than convective transport, sorption is the most important factor influencing waste movement. The sorption coefficient (Kd) at any time or spatial location is a function of the macro-ion concentration (for Hanford these are Mg^{2+}, Ca^{2+}, K^+, and Na^+), pH and soil sorptive characteristics.

Considerable soil-waste reaction work has been conducted to determine the relationship of the Kd and macro-ion concentrations. A soil-sorption model, which solves the one-dimensional convective transport equation for steady flow fields, was developed to evaluate and refine these relationships. Na^+, K^+, Ca^{++}, and Mg^{++} have been successfully handled by the use of ion exchange equations that have been developed. The system can be extended to other solution ions. Known carbonate and sulfate precipitation and association equilibria are used to predict these equilibria. The model has also been used to evaluate the experimentally determined sorption coefficients.

Since laboratory soil column work has been conducted at Hanford for many years, the work accomplished under this program can be readily compared to the previous accomplishments. Figure 8 is intended to graphically indicate the progress which has been made on radiocontaminant transport through research on this program. A column experiment was conducted using a fabricated waste solution (typical of those encountered at Hanford). The triangles shown in Figure 8 are the ^{85}Sr relative concentrations measured in the column effluent. The dashed and solid curves represent predicted values using the soil-sorption model. For curve 1, it is assumed that the Kd is constant (the approach used prior to the inception of this development program); i.e. the Kd is independent of the macro-ion concentrations. Curve 2 represents the breakthrough using a Kd that is a function of macro-ion concentrations. The Kd's can be obtained through either small column or batch techniques. As can be seen, significant errors in predicting radiocontaminant movement can occur if the Kd is assumed independent of macro-ion concentrations. This comparison shows that the approach being used does an excellent job of describing the chemistry of the soil-waste interactions.

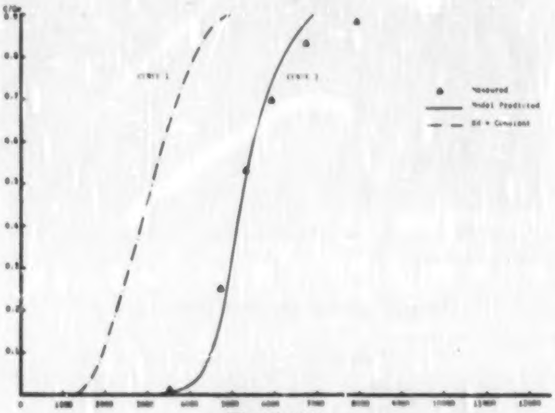


Fig. 8. Relative concentration of ^{85}Sr from a Burbank sand subsoil column as a function of effluent volume.

Model Application

Concurrent to the development of the integrated model system described above, a unique man-machine interactive computer system has been developed for use in application of the models to field problems. The objective of this system is to provide the tools with which an engineer, who is not a computer expert, can analyze waste management alternatives through efficient utilization of the models previously described. Figure 9 is a photograph of this system. From left to right are (1) graphic digitizer, (2) CRT-light pen, (3) teletype, and (4) PDP-9 digital computer. The PDP-9 computer is being linked to a much larger Univac 1108 computer as shown in the schematic diagram of the man-machine interactive computer system in Figure 10. The dashed lines represent proposed additions to the system. A high speed printer-plotter is presently being added to the system. Problems will normally be input to the computer through one or more of the devices and transmitted to the larger computer for calculation. The results would then be transmitted back to the smaller system for analysis and output.

The graphic digitizer is an input device which permits input of analog data (maps, charts, etc.) directly to storage in the PDP-9. This results in extremely rapid and accurate input of information. Input data changes can also be readily input with this system without complicated revision of the originally stored information.

Fig. 9. Photograph of the man-machine interactive computer system.

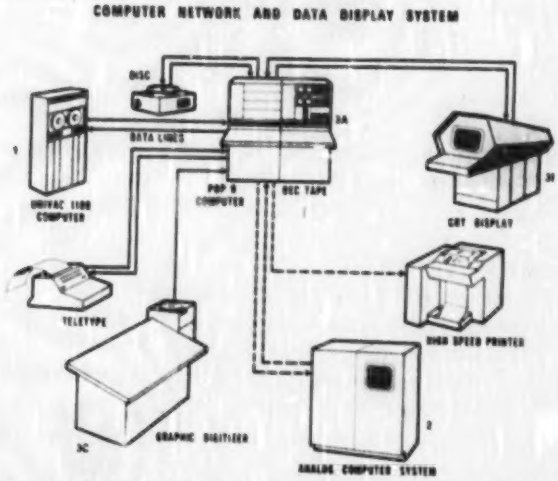

COMPUTER NETWORK AND DATA DISPLAY SYSTEM
DISC
3A
DATA LINES
1
UNIVAC 1108 COMPUTER
PDP 9 COMPUTER
DEC TAPE
3B
CRT DISPLAY
TELETYPE
HIGH SPEED PRINTER
2
3C
GRAPHIC DIGITIZER
ANALOG COMPUTER SYSTEM

Fig. 10. Schematic diagram of the man-machine interactive computer system.

The CRT is a device which displays problems visually, and utilizing the light pen, the engineer-operator interacts directly and in real-time with a problem solution and analysis. The power of such a system to the manager or engineer/user is difficult to convey on paper. The problems are set up and input in rapid and accurate fashion. Solutions are obtained on a rapid turn around basis and displayed for the user. The user immediately is able to evaluate the results, make changes and ask for new solutions. Of particular importance is the ability to inject the experience and knowledge of the user into the problem solution. When an acceptable solution is achieved, the results can be printed on a line printer or plotter. This system development is being carried out in conjunction with the model development and will be fully operational at the same time as the models themselves. The system is already serving an important function in the model development effor, as mentioned earlier.

Fig. 11(a). Reference map of the Hanford reservation.

Fig. 11(b). Contours of the Hanford water table.

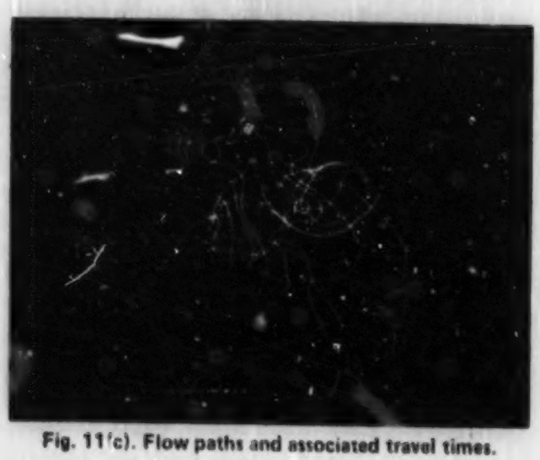


Fig. 11(c). Flow paths and associated travel times.

Fig. 11. Computer generated displays associated with the calculation of ground-water travel times.

Figures 11 through 13 show some additional photographs of displays generated on the CRT display unit. Figure 11 shows the sequence the engineer uses to instantaneously calculate ground-water contours, flow paths and travel times. Figure 11(a) shows the reference display of the reservation. In the contour mode the operator can plot contours of either measured or predicted water tables which are digitally stored on the disc unit (Figure 11(b)). The values of the contours that are plotted are input through the keyboard of the display unit. Contours can readily be added or deleted by the operator. In the travel time mode, the starting location of the flow path is input through the digitizer. Then the flow path is instantaneously calculated and displayed along with the associated travel time (Figure 11(c)). The travel time displayed on the CRT is associated with the last flow path that was selected. With this program, the engineer can rapidly assess the impact of management alternatives on the water table elevation, flow paths and travel times.

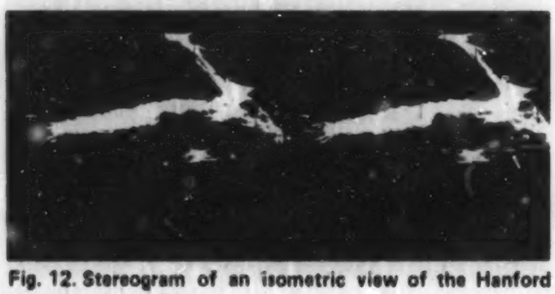


Fig. 12. Stereogram of an isometric view of the Hanford ground-water surface.

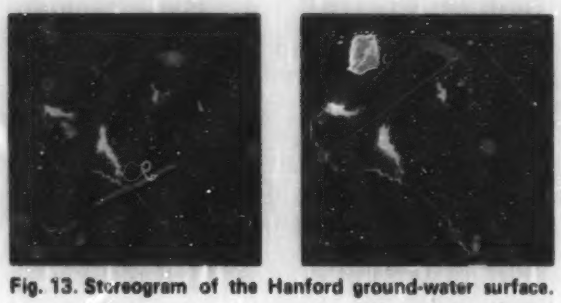


Fig. 13. Stereogram of the Hanford ground-water surface.

Figures 12 and 13 are self-explanatory and represent another form of output which is available. These photographs were taken from a memory scope display.

ACKNOWLEDGMENTS

The author would like to acknowledge the engineers and scientists who were responsible for the development of the integrated model and the display systems: A. E. Reisenauer, hydraulic models; R. C. Routson and R. J. Serne, soil-waste interrelationships; A. Brandstetter and R. G. Baca, transport models; D. R. Friedrichs, L. E. Addison and H. P. Foote, data models and display programs; L. H. Gerhardstein, system software; and R. D. Mudd, general assistance. Although listed by their major area of contribution, there was considerable integration and combined effort in each of the categories by the individuals listed above. The author would also like to acknowledge the continued support of the program by the Atlantic Richfield Hanford Company, especially R. E. Isaacson, D. J. Brown and M. D. Veatch.

DISCUSSION

The following questions were answered by D. B. Cearlock after delivering his talk entitled "A Systems Approach to Management of the Hanford Ground-Water Basin."

Q. *Now that you have the models working, suppose the power company came to you to do an environmental impact analysis of waste discharge from a planned nuclear reactor plant. Assuming that only routine soil geological maps were available for the area, how much time, about how many man-years effort, would be required to apply your analysis to this situation?*

A. It is difficult to estimate the effort required for a job without a more detailed elaboration of the problem. The cost is directly associated with the complexity and size of the ground-water basin, the various components of the system of models to be used and the limitation of the assumptions used in the models. If simplifying assumptions can be made and only a portion of the system of models used, application costs would be considerably less than if it was necessary to use the entire system as described in the paper. As the complexity of the system and the accuracy requirements increase, the associated costs will increase.

Q. *You indicated you have data to verify water movement and travel time. Would you elaborate on those data? And allied with that is this question. What is your evidence that the impervious strata in one of your slides are really impervious?*

A. A water quality surveillance program, which has been conducted since the inception of the AEC activities, has provided the data for verifying the water movement patterns and the travel times. As mentioned in the paper, the agreement between observed and measured movement patterns is good. However, these verification results are preliminary, and detailed laboratory and field verification studies are presently being conducted. Emphasis to date has been directed predominantly toward developing the complete system of models.

Both geologic and hydrologic data indicate the existence of an impervious strata over much of the project. Geologic data indicate the presence of tight silt-clay layers although the continuity of these layers has not been established.

Q. *Here's another part of a question. Where is the natural discharge of the lower aquifer?*
A. This is being researched by ARHCO and USGS.

Q. *Can your program solve other kinds or types of tank failure in place of the rather unlikely sudden removal of the whole tank bottom and would these give significantly different results?*
A. Other types of tanks and tank failures can be modeled. The models were designed to be completely flexible so that, in general, any type of tank leak or tank failure could be modeled. There are about 25 different shapes of boundaries that can be used in describing a tank facility.

After analyzing the results of the rupture of the entire bottom of a tank, we believe a small leak would result in faster penetration to the water table and higher concentrations of nuclides in the ground water if the leak were allowed to persist; however, this is unsubstantiated by either modeling or observations.

Q. *Does your, or did the pumping well cause any subsidences in the area of the plant and the storage tank and, if so, what measures were taken to correct it?*
A. The pumping wells we refer to are test wells used for transmissibility determinations and are not water-supply wells; hence, one should not anticipate subsidence.

Q. *What methods would you use or will you use to solve the differential equations for hydraulic dispersions in the natural system?*
A. The transport equation is essentially a first order equation since in ground-water systems, convection is usually more significant than dispersion. Therefore, use of numerical techniques for second order equations can result in numerical dispersion. To minimize numerical dispersion we have adopted a hybrid approach first developed in the petroleum industry. It involves using both Lagrangian and Eulerian systems. The convective transport is solved in the Lagrangian system and dispersion is solved in a Eulerian system. We have tested the method against analytical solutions and the agreement was good.

Q. *Are values of porosity and dispersion coefficients required for your models and, if so, how were they determined and what is the sensitivity of the model for variations in these parameters?*
A. Both porosity and dispersion coefficients are required in the model. We are presently using dispersion coefficients measured in laboratory soil columns. At specific sites on the reservation, the effective porosity has been estimated from travel time data. We have not conducted sensitivity analyses with respect to porosity and dispersion coefficients.

Q. *Do you believe that our presently available methods of obtaining reliable field data justify the utilization of such elaborate mathematical models?*
A. Yes. Otherwise we would not be developing the models. The models are being used to identify where additional data are required to improve the understanding of the aquifer. Use of the models in this way minimizes the collection of data that are not directly useful in understanding the ground-water system. This approach has substantial advantages over the classical approach of conducting extensive field measurement programs prior to modeling the system. In addition, the preliminary verification results presented in the paper are very encouraging.

Q. *Can your analysis which now considers the effect of ion exchange on ion transport also incorporate the effects of such processes as precipitation and oxidation?*
A. Yes. The model presently handles some precipitation reactions. For these reactions it is assumed that the precipitate does not alter the permeability.

Q. *Isn't the porosity important for travel time? It appears that only transmissivity was used.*
A. Yes, porosity is important. We have been using an effective porosity estimated from field measurements and tests. We have also assumed the effective porosity is constant over the entire project because of the lack of data. The effective porosity has been observed to be considerably less than the bulk porosity in certain areas. However, these data are limited.

Q. *How much does the porosity vary?*
A. The bulk porosity varies approximately between 30 and 45 percent. In contrast, the calculated permeability varies by 4 to 5 orders of magnitude. We do not have the data available to determine how much the effective porosity varies.

Salty Ground Water and Meteoric Flushing of Contaminated Aquifers in West Virginia[a]

by Benton M. Wilmoth[b]

ABSTRACT

Salty ground water is commonly encountered at relatively shallow depths of 100 to 300 feet beneath the major stream channels in the western half of West Virginia. Because of the wide distribution of salty ground water and connate brine at various depths, it is difficult to distinguish natural contamination from that caused by subsurface industrial activities. Natural changes in quality apparently are minor. The available historical data indicate no large-scale natural variations in salt content during the period of record. Histories of some water well developments show unnatural large-scale increases in salt content from various industrial activities that affect the fresh water zones. Some records also reveal decreases in salt content after the source of the salt was eliminated or after the subsurface activity responsible for artificial migration of the salt water was stopped.

Artesian brine contaminated a fresh water aquifer in Fayette County. Chloride content changed from 53 mg/l to more than 1,900 mg/l in a period of 5½ years. When pumping was stopped, chloride content decreased to 55 mg/l in 10 years.

Heavy pumping of well fields in Charleston during 1930 to 1956 accelerated migration upward of salt water. Chloride content increased from less than 100 mg/l to more than 300 mg/l in some wells and to more than 1,000 mg/l at individual wells. Pumpage has declined greatly since 1956 and chloride content has decreased below 200 mg/l at some of the contaminated wells.

In an oil field of Kanawha County, a water well was contaminated by salt water accelerated by subsurface activities. Chloride content increased from less than 100 mg/l to more than 2,900 mg/l within 2 months. After the oil-field activity was curtailed, chloride content decreased to 190 mg/l in about 2½ years. Road salt piles contaminated a carbonate aquifer in Monroe County. Chloride concentrations in wells located 1,500 feet from the piles increased from 185 mg/l to 1,000 mg/l in 5 years. The greatest change was 1,000 mg/l in 1969 to 7,200 mg/l in 1970 when the salt storage area was enlarged. All salt piles were removed in late 1970 and within 2 months chloride content decreased to 188 mg/l.

One of the most difficult problems in subsurface hydrology is to predict the movement of a contaminant in ground water when concentrations are decreased by dilution. The problem is further complicated if the contaminant, such as salt water, also occurs naturally in adjacent aquifers at a wide range of concentrations, velocities, and depths. Consequently to determine when salt water has occurred naturally and when it is the result of subsurface industrial activities is a formidable task. Predictions of future subsurface conditions are likewise extremely difficult.

Sedimentary rocks of Pennsylvanian and Permian (?) ages of the western half of the State form a complex, alternating series of conglomerate, shale, siltstone, limestone, and coal strata. The rocks are gently folded along subparallel axes that trend generally northeastward. These flexures tend to obscure the general regional dip of the rocks to the northwest. Because of the folding and subsequent erosion, some of the older brine-bearing rocks are close to the land surface along the axial centers of major anticlines. Although ground water has been obtained at depths of more than a mile, test holes usually encounter little water below 2,500 feet. This is about the top of the zone of rock flowage where the weight of the overlying rock column tends to close pore space.

The majority of the shallow rocks that are weathered and fractured at depths ranging from 25 to 300 feet yield ground water. The major developed aquifers and most of the ground-water pumpage are within this zone. Intergranular or primary permeability and fracture or secondary permeability both contribute to shallow ground-water occurrence but little evidence is available to indicate the predominant form. Sandstone and conglomerate usually have the highest permeability because either the primary permeability is predominant or the secondary permeability is developed to a larger degree. These are the predominant water-bearing rocks. Highly fractured sandy shale within 100 to 300 feet of the land surface can also yield moderate amounts of ground water. Minor beds of thin nodular limestone, fire clay, and coal are aquifers in local areas only.

Large areal exposures of limestone and dolomite in the eastern part of the State are excellent major aquifers. In general, throughout the State, aquifers that are considered practical at the present time for development lie within about 500 feet of the land surface; however, the average depth of existing wells is still only about 125 feet.

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[a] Presented at the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

[b] Geologist, Environmental Protection Agency, 303 Methodist Building, Wheeling, West Virginia 26003.

Meteoric fresh ground water moves by gravity from upland intake recharge areas through fractures and interstitial openings in a very complex flow system. The configuration of flow through various kinds of stratified rocks with complicated vertical and lateral hydrologic boundaries can only be generalized. The ground water may remain only a few days in the shallow rocks before it is discharged as springs or seepage; or it may recharge deep artesian reservoirs and remain for many thousands of years becoming more mineralized with time. The velocity of flow may range from a few inches to several hundred feet per year.

Although some ground water in the outcrop areas of aquifers is unconfined, artesian conditions exist below where the water becomes confined and is known to exist at depths of more than 2,000 feet. The water-bearing rocks form a series of aquifer systems, each composed of several hydraulically connected beds. The amount of hydraulic connection ranges from direct or free to very little, due to relatively impermeable intervening formations.

If the stream channels of the western half of the State act as sumps for the natural discharge of both fresh and salty ground water, the interface or top of the salty ground water apparently tends to "cone up" toward the stream and then lie at successively greater depths with increasing distance away from the valley beneath the hills and ridges.

The saturated, unconsolidated alluvium bordering the major river valleys also contains salt water in certain areas. Segments of former stream channels in the bedrock of present major valley floors are filled with highly permeable sand and gravel of Pleistocene age. These sand-and-gravel-filled depressions along the Ohio River Valley in Cabell, Tyler, Brooke, and Hancock Counties apparently are intercepted by the salt water migrating from the underlying bedrock.

Usually, the shallow saturated rocks contain the fresh meteoric ground water, and the rocks below contain the salty ground water. The shallow salty ground water is essentially a zone of diffusion or mixing between the fresh ground water and the deep connate brines. These fluids generally cut across geologic contacts in response to natural hydraulic conditions or to the changes in conditions imposed by subsurface industrial activities.

Chemical character of fresh ground water is controlled primarily by the chemical composition of the soluble rock minerals of the aquifers. Consequently, both local and regional lithologic differences can produce differences in the chemical quality of ground water. Fresh ground water contains less than 1,000 mg/l of dissolved solids, whereas shallow salty ground water usually contains 1,000 to 3,000 mg/l of dissolved solids. Fresh ground water from shallow bedrock aquifers is chemically suitable for most domestic uses. The water is mostly of the calcium, sodium, or magnesium bicarbonate type and is alkaline, but the encroachment of brine into the fresh-water aquifers changes the water to a sodium chloride type.

In most areas of the western half of the State, the salty ground water occurs 100 to 300 feet below the altitude of the major stream channels. The chloride concentration of the ground water continues to increase with depth as the flushing effect of the circulating fresh meteoric ground water diminishes. At depths of 1,000 to 5,000 feet, highly concentrated brines containing 30,000 to 100,000 mg/l of total dissolved solids are encountered (Price, Hare, McCue, and Hoskins, 1937, pp. 28-32). These brines were derived from sea water trapped in the original rock-forming sediments. At these depths, the natural migration is extremely slow. The various processes of chemical concentration and modification of the sea water are not completely understood.

In totally undeveloped areas, where there has been no deep drilling, the natural vertical migration of salt water apparently is extremely slow. Perhaps any natural changes in the quality of both fresh and salty ground water in these areas are minor over several hundred years. The few historical data available for specific aquifer areas indicate no large-scale natural variations in salt content during the period of record (Wilmoth, 1970). Much salt-water migration into shallow rocks, therefore, is a natural phenomenon from a very long period of interformational seepage of artesian brine out of deep formations. Apparently, this migration has occurred over several million years of geologic time.

Salt water seeps and springs in several counties were used by the Indians and the pioneer settlers to obtain salt. The best known occurrence of salt water discharged as natural springs is in the Kanawha River valley near the mouth of Campbell's Creek at Malden, Kanawha County. Here a major geologic structure, the Warfield anticline, caused geologically older brine-bearing rocks to crop out. Historical records (Summers, 1935) show that these salt water springs were used by the Indians in the 1700's. Archeological evidence indicates they used brine as early as the year 1000, but they may have obtained brine or salt in the general area for more than 10,000 years (Broyles, Betty, personal communication). The early settlers in Kanawha River valley improved the springs and later made crude drilling explorations in the area by means of tilt pole rigs. Deep drilling methods and equipment were improved before the Civil War, and large amounts of salt were produced in the valley (Howe, 1845). Most of the brine was obtained from deep wells tapping the Pottsville Group at depths of several hundred feet.

All of the conditions which made fresh ground-water aquifers vulnerable to the encroachment of salt water are not known. The best information is obtained from records at fresh water well developments which experienced salt water encroachment after many years of successful operation. While the subsurface environment of these areas cannot be described accurately, it is possible to define the general occurrence of the salty ground water and its relation to the fresh ground water. In some areas, deep drilling and related subsurface industrial activities have merely accelerated the vertical and lateral migration of natural formation fluids. Consequently, these fluids are now present in certain shallow aquifers in greater quantity and concentration than under the original natural conditions. In the past few decades rapid, unnatural, salt water migration toward the land surface has been mostly by vertical leakage along hundreds of unplugged wells and test bores. These holes were put down during exploration for brine, oil, gas, water, and coal. Commonly, the holes were abandoned uncased and improperly plugged. The formation fluids of brine and related hydrocarbons flowed up the holes in response to the artesian pressure under which they were confined. These essentially open holes can act as nearly infinite vertical rock permeability and the natural protection from rapid fluid migration offered by thick sequences of shales and other confining strata is lost. In many areas, salt water under artesian pressure has migrated into developed fresh water aquifers when casing was removed from an abandoned deep well.

Because of the extensive distribution of brine and salty ground water at a wide range of depths in the western part of the State, it is difficult to determine how much of the salt water occurs naturally and how much has been accelerated artificially by subsurface industrial activities. Salt water can leak and build up for many decades immediately below a fresh-water aquifer and still not pose a problem to shallow drilled domestic water wells pumped at low rates. However, waste brine disposal, water flooding, repressuring, or hydraulic fracturing can trigger the salt water encroachment of these fresh water zones. Solutions to and remedial actions for such contamination problems become more difficult with greater distances of aquifer area and longer periods of time involved.

Most areas of consolidated sedimentary rocks are underlain by two or more aquifers in which water levels are of quite different elevation. As a result, some natural seepage or leakage occurs between the various aquifers. A lower artesian pressure in an aquifer indicates that ground water from an overlying or underlying aquifer of higher pressure may move into it through confining beds. The direction of this natural interformational leakage can also be reversed by pumping and changing of heads in the aquifers. High-capacity pumping from fresh water zones may lower the head in the rocks to levels below the artesian head of the salty ground water. The salt water may then migrate into the fresh water aquifer if the zones are hydraulically connected.

Records of ground-water quality in the bedrock aquifers at Charleston, Kanawha County indicate that withdrawal of large amounts of fresh water was a significant factor in the accelerated encroachment of salt water. From 1930 to 1956 pumpage of ground water was heavy, and salt water encroachment was accelerated (Figure 1). The maximum withdrawals occurred during 1940 to 1950 (Wilmoth, 1965). Chloride content of ground water increased from less than 100 mg/l to more than 300 mg/l in several well fields and to more than 1,000 mg/l at individual wells (Wilmoth, 1970). Pumpage gradually declined from 1956 and by 1966 was extremely small with only periodic use of one or two wells. Chloride content of ground water at some of the contaminated wells had decreased below 200 mg/l by 1970 (Figure 2). This is about 14 years from the last year of heavy ground-water pumpage.

Extensive areas of fresh ground-water aquifers have been contaminated by vertical migration of artesian salty ground water into fresn water through unplugged test bores and improperly abandoned wells. In Fayette County, the chloride content of ground water in a fresh water sandstone aquifer of the Pottsville Group increased from 53 mg/l to more than 1,900 mg/l within 5½ years (Figure 3). Pumpage in the aquifer was essentially stopped when the principal water well was shut down because of the high salt content. Pumping of the well apparently helped to accelerate the contamination, because within about 10 years natural meteoric flushing had reduced the chloride content to 55 mg/l in part of the aquifer.

In an area of Kanawha County the secondary recovery of oil by water flooding has resulted in a higher piezometric level of the brines in rock units below the fresh water aquifers. This has caused an accelerated migration of the brine upward into the fresh water.

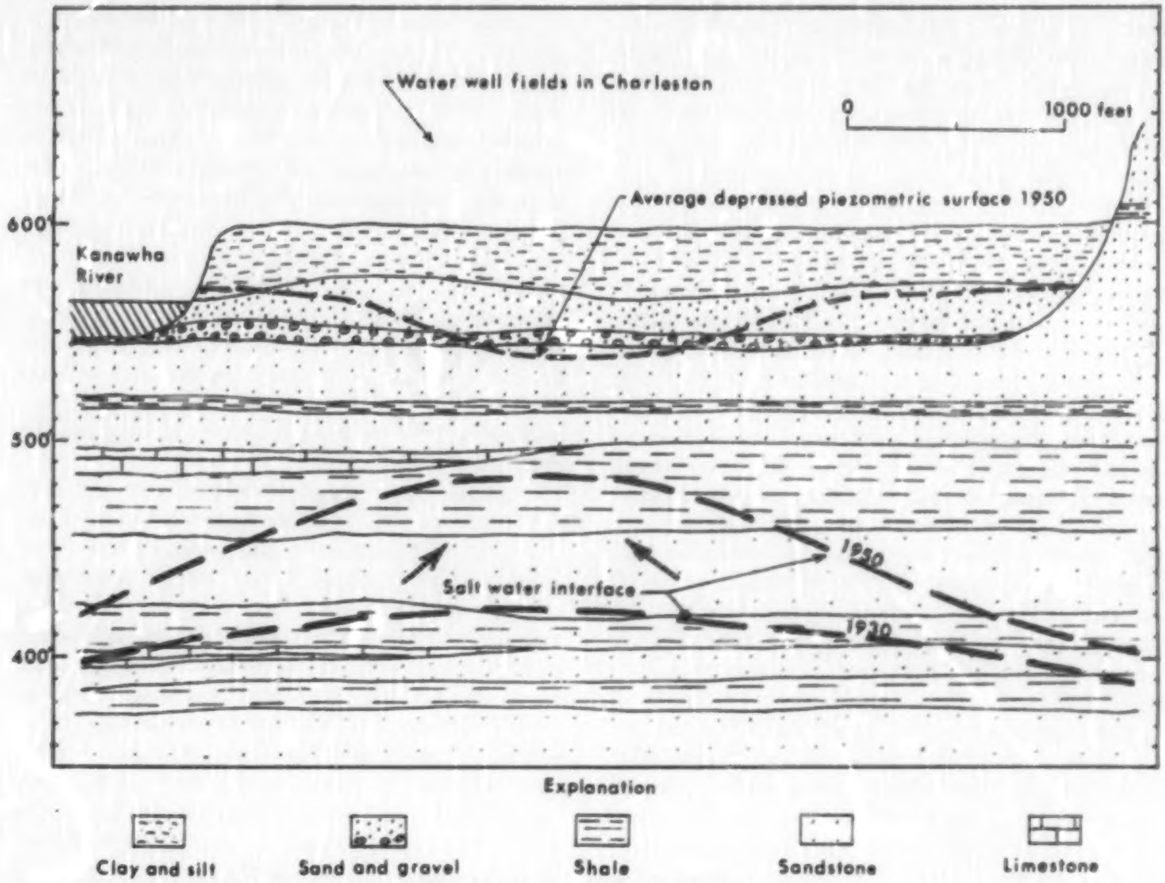
Water well fields in Charleston
0
1000 feet
Average depressed piezometric surface 1950
600'
Kanawha River
500'
1950
Salt water interface
1930
400'
Explanation
Clay and silt
Sand and gravel
Shale
Sandstone
Limestone

Fig. 1. Changes in elevation of salt water interface, Charleston, Kanawha County.

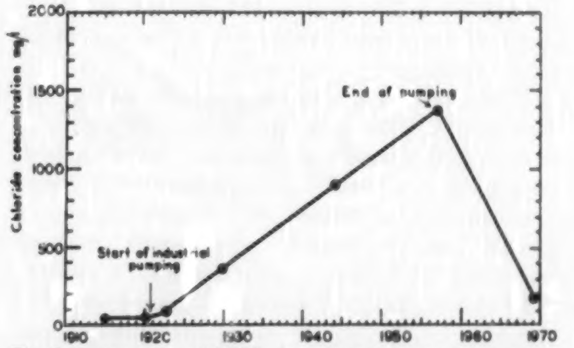

Fig. 2. Changes in chloride in ground water from overdevelopment of aquifer, Charleston, Kanawha County.

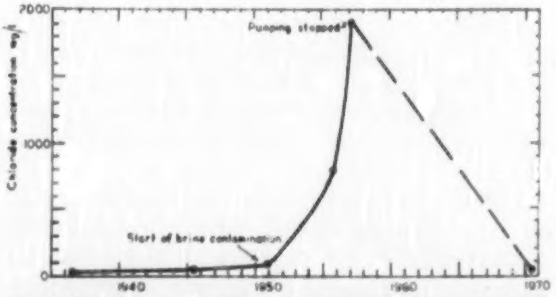

Fig. 3. Changes in chloride in ground water from open-hole migration of artesian brine, Fayette County.

Unnatural fluctuations in chloride content were observed in ground water from several wells in this area. The fluctuations in quality apparently are related to the rate and pressure of brine injection. In one domestic water well supply the natural chloride content in 1967 was 32 mg/l. Shortly after secondary recovery of oil was started the chloride concentrations began to increase. Within 9 months the chloride content had increased to 250 mg/l, and within 11 months the concentration was 1,140 mg/l (Figure 4). After this maximum chloride level was reached, the concentrations began an uneven but rather steady decline. After 2½ years of general decline the chloride content was 450 mg/l early in 1971. Apparently changes were made in the repressuring operations in the oil field. Then

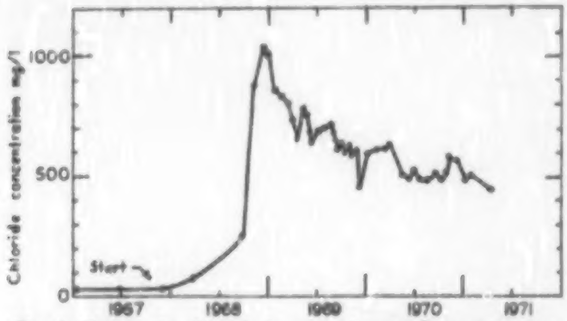

Fig. 4. Changes in chloride in ground water from repressuring of oil field, Kanawha County.

natural meteoric flushing of the shallow aquifers helped to remove enough of the chloride for the wells to be utilized.

Oil field operations also caused salt contamination of a fresh water aquifer near Wallace, Kanawha County. In late 1967 the natural chloride content of the aquifer was 100 mg/l. Within 2 months after the start of the subsurface oil well operations, the chloride content reached 2,950 mg/l (Figure 5). The oil well operation was altered and chloride concentration began to decrease rapidly. Within 2 months the concentration was 950 mg/l. During the next 2½ years the chloride content declined to 190 mg/l.

In the oil fields of Roane County, pressure injection disposal of produced waste brine into the Salt Sandstone of the Pottsville Group has raised the piezometric level of the natural brine in this formation. Because the overlying shallow fresh water zones are hydraulically connected to the injection zone, there has been extensive damage to the fresh ground water. In some areas, brine contamination has been rapid with chloride content increasing from less than 25 mg/l to more than 1,500 mg/l within several months. Unnatural cyclic changes in quality have occurred in many private ground-water supplies. In one part of a fresh water aquifer, the chloride concentration of less than 50 mg/l increased to 1,150 mg/l in a period of 19 months (Figure 6). After the subsurface oil-field brine disposal operations were altered, the chloride content declined to 68 mg/l within 17 months.

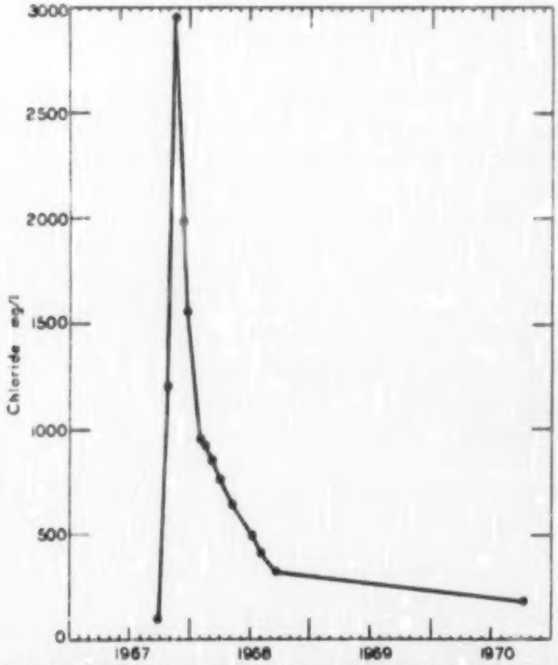

Fig. 5. Changes in chloride in ground water from oil well operations, Kanawha County.

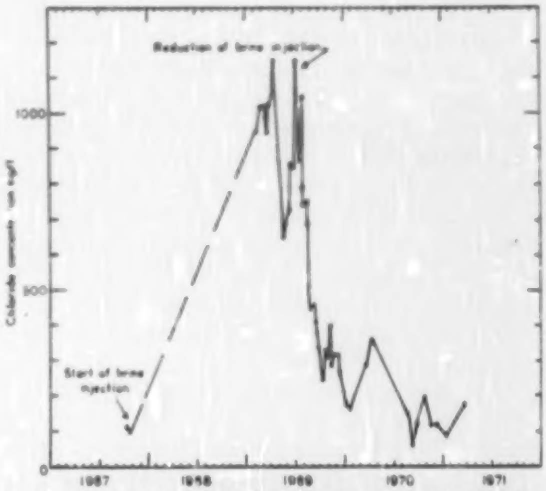

Fig. 6. Changes in chloride from pressure injection of brine, Roane County.

Soluble chemicals such as highway deicing salt are causing the deterioration of ground-water quality in certain shallow fresh water aquifers in the State. Chemical analyses show unnatural cyclic changes in chloride content. Although the aquifer areas of deteriorated water quality are local, reported incidents of such contamination are increasing every year.

The amount of salt used annually for ice and snow control on highways continues to increase. This highly soluble material is now being recognized as a contaminant that easily migrates into shallow fresh water aquifers with natural recharge. In several States, water quality control specialists are observing possible cumulative effects of the salt load on the hydrologic system (Walker, 1971). Apparently most of the salt is transported during thaw periods by runoff to the nearest stream and is progressively diluted downstream. Chloride concentrations of more than 10,000 mg/l have been observed in the runoff from heavily salted areas of Grant and Raleigh Counties. Salt carried by natural recharge may require several months or years to percolate to aquifers and move laterally to pumping water wells. Although the actual risk of contamination from salt spreading is not known at this time, it is estimated that more than half of all the water wells in the State are located within 100 to 500 feet of a road that receives some salt treatment.

Shallow fresh water aquifers in carbonate rock terrane are developed extensively for rural farms and businesses in the eastern part of the State. The principal source of recharge is precipitation which enters the aquifer via solution crevices and sinkhole depressions. The rate of travel from recharge areas to water wells may be rapid with very little filtration occurring. Potential contamination of such aquifers should be suspected if the groundwater turbidity increases after heavy rainfall.

An unusual case of salt contamination of fresh ground water from the land surface occurred near Union, Monroe County. The history of water quality in this area illustrates the high contamination risk of shallow carbonate aquifers. There is no natural near-surface salty ground water in the area, nor any gas wells or other deep drilling. Partial chemical analyses indicate that the natural chloride content of the fresh ground water in the area averages about 25 mg/l.

Several hundred tons of rock salt stored directly on the land surface were also unprotected from precipitation and runoff. Water wells located about 1,500 feet laterally and downgradient were subsequently contaminated with such high concentrations of chloride that the water was unfit for use. The chloride concentration in one water well steadily increased to 1,000 mg/l in about 5 years (Figure 7). The period of greatest change was 1,000 mg/l in 1969 to a high of 7,200 mg/l in 1970. The wells in this area are 73 to 79 feet deep and tap highly permeable fractured and solutioned carbonate aquifers. The natural gradient of the water table was from the salt storage area toward the wells. The contaminated ground water moved downgradient through the aquifer toward points of natural discharge. Interception of the flow by the pumping wells resulted in extreme degradation of several supplies. In late 1970, the salt was removed from the ground and stored in a protective building. During the 2 months following the salt storage removal, chloride concentrations in the monitored contaminated well decreased to 188 mg/l.

In Grant County, an investigation was made of salt contamination of a shale aquifer tapped by a drilled well 160 feet deep. Apparently the contamination in this well was from the spent salty backwash from a zeolite water softener, which discharged into a dry sump located upgradient from the water well. Natural ground-water recharge carried the salt downgradient toward the pumping well. The natural chloride content of the ground water in this aquifer was determined in 1962 to be 9 mg/l. Within 16 months after the zeolite water treatment unit was installed, chloride content had increased to 580 mg/l (Figure 8). Early in 1970, some 3 years after the brine was periodically discharged to the sump, the chloride content had reached 1,650 mg/l. Early in 1970 the treatment unit was shut down and brine disposal was stopped for several months. Within a few weeks, the rate of change in chloride content was decreased significantly. From January 1971 to May 1971, the chloride content actually declined from 1,712 mg/l to 1,650 mg/l.

Because the records of some salt-contaminated well developments show decreases in salt content after the source of the salt was eliminated, there is

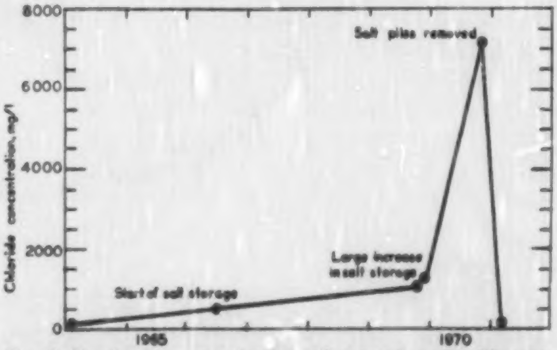

Fig. 7. Road salt contamination of ground water, Monroe County.

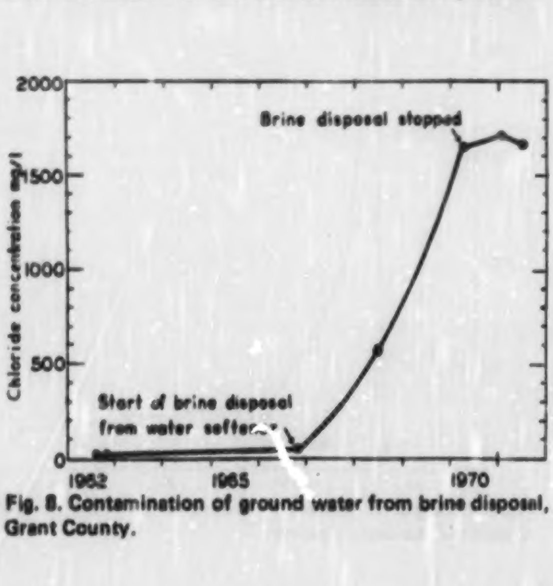

Fig. 8. Contamination of ground water from brine disposal, Grant County.

reason to consider remedial work in certain unnaturally contaminated aquifers.

If the abandoned wells and test bores could be properly plugged and cemented, the source of the salt water should be effectively stopped. Thereafter, the natural meteoric ground-water recharge to the fresh water zones should eventually flush out the salt water. Then pumping of the water wells tapping the aquifer should actually accelerate the flushing action.

Because the ground-water aquifer is not seen at the land surface, much pollution often occurs before it is known. The public is often unaware that certain industrial activities or incorrect pumping can pollute aquifers. The single most important aspect of ground-water quality control is the prevention of contamination rather than attempts to correct problems after they occur. Public education for constant surveillance of activities that can result in contamination is certainly an important need to be considered.

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DISCUSSION

The following questions were answered by Benton M. Wilmoth after delivering his talk entitled "Salty Ground Water and Meteoric Flushing of Contaminated Aquifers in West Virginia."

Q. *In the example where the water softener discharge was recycled, what was the original hardness of the water?*

A. I don't remember exactly, but it was less than 200 mg/l. The well at this facility taps a shale aquifer.

Q. *Does West Virginia have a regulatory agency at present to insure the adequate construction of oil wells and brine pits for the protection of potable ground and surface water supplies, and, if not, why not?*

A. Yes, the State has the Division of Oil and Gas that regulates oil and gas well construction, operation, and abandonment. The State Division of Water Resources is charged with protection of the water resources.

Q. *I think each of us from our own States recognizes that we have a legal authority, but sometimes we don't have the enforcement personnel to do the job the law says we can do. Here's a question. Why were your brine heads converted to fresh water equivalents?*

A. This was done for diagrammatic purposes to illustrate how the head of the salty ground water does override the head of the fresh water zones under certain hydrogeologic conditions.

Q. *In one of your slides showing the close relationship of oil and saline shallow ground water, was the oil production from the shallow Pennsylvanian sands or from the deeper zones?*

A. Oil production was from the deeper Big Injun formation of Mississippian age. Some abandoned holes must be hydraulically connected to the shallower Salt Sandstones of Pennsylvanian age, because some holes are uncased and other holes have deteriorated casing.

Q. *Have you been able to map or identify most of the natural discharge area for the brine and map the natural regional movement for the brine?*

A. No, at present we merely know general areas where brine is discharged. There is a cooperative study by the State and Federal Geological Surveys to map the salt water–fresh water interface. This should be of significant aid to the Division of Oil and Gas in regulating the casing and cementing of new wells.

Q. *What do you consider to be the future for ground-water use in the Kanawha River Valley and will significant development be possible in view of the problems?*

A. At present we are limited to the relatively shallow consolidated aquifers for ground water not high in chloride. Yields of 50 to 200 gpm are available at depths of about 150 feet. The unconsolidated alluvium produces 50 to 150 gpm to standard vertical screened wells in selected places between

Charleston and Point Pleasant. Higher yields of 200 gpm may be available in downstream areas of Mason County.

Q. *One of your slides showing the occurrence of saline ground water showed that it was shallow in the western half of the State and deeper in the eastern half. Is the reason that there is no shallow saline ground water in the eastern half of the State because the bedrock contains no shallow aquifers there, or because the water is fresh there?*
A. The history of ground-water development shows that deeper aquifers in the eastern part of the State contain fresh water. Apparently the natural salty ground water is nearer the land surface towards the Ohio River area which limits fresh ground water to the relatively shallow zones.

Q. *Was the surface soil removed from the chloride storage sites to speed the recovery of the aquifer?*
A. I doubt it. I believe that the storage areas were swept clean of solid salt with brooms. New salt storage facilities will be protective sheds, perhaps with impermeable floors. Also some salt may be stored in plastic bags.

Q. *Here's a question that has to do with so-called impermeable zones. Was the shale heavily fractured, or did the chlorides readily move through these "impermeable" zones?*
A. Most of the shale was very heavily fractured. The silty shale or sandy shale, almost always will produce water. Certainly not as much as sandstone, but enough for domestic supplies.

Probable Impact of NTA on Ground Water[a]

by William J. Dunlap, Roger L. Cosby, James F. McNabb, Bert E. Bledsoe, and Marion R. Scalf[b]

ABSTRACT

Laboratory studies were employed to investigate the fate and effect of NTA both in ground waters and in soil profiles overlying ground waters.

Studies of the sorption of NTA by sand, loam, and clay-loam soils indicated that sorption of NTA on soils could slow its movement into and through ground waters. Sorption will probably not be sufficient to prevent or greatly reduce potential pollution of ground water by NTA used as a detergent builder.

Soil column studies were employed to investigate the degradation and effect on metals of NTA infiltrating through soils. These studies indicated: NTA infiltrating through most unsaturated soils likely would undergo rapid and complete degradation and contribute only inorganic nitrogen compounds and carbonate to ground waters; NTA infiltrating through saturated soils would probably experience only very limited degradation, with a major portion entering ground water intact; any NTA which escaped degradation during infiltration through soils could transport such metals as iron, zinc, chromium, lead, cadmium, and mercury from soils into ground waters.

Studies with model aquifers constructed from natural aquifer sand indicated that NTA would likely undergo slow degradation in essentially anaerobic ground-water environments, with production of CO_2, CH_4, and possibly other organic compounds.

INTRODUCTION

Ground waters in the United States are being increasingly subjected to possible pollution by a wide array of synthetic organic chemicals entering the environment as a result of the needs and demands of modern society. Nitrilotriacetic acid (Figure 1) is a synthetic organic compound worthy of special concern in regard to its possible impact on ground water because of the magnitude of potential usage of this compound, both from the standpoint of quantity and geographical distribution.

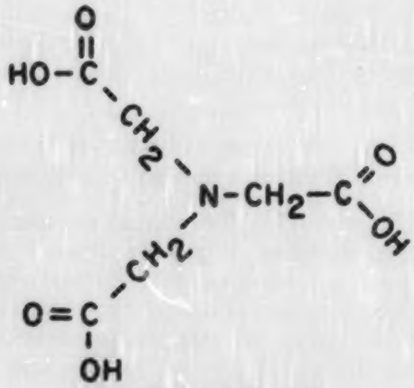

Fig. 1. Nitrilotriacetic acid.

Nitrilotriacetic acid (called NTA) is currently the leading candidate to replace the condensed phosphates now used as "builders" in the formulation of synthetic detergents. Elimination of phosphates from detergents is sought because of their probable contribution to the eutrophication problem plaguing many of our surface waters. If NTA were to replace only half of the condensed phosphates currently used in detergents in the United States, over a billion pounds of this substance would appear in our waste waters annually. Furthermore, the intended use of NTA in detergents would insure its distribution throughout the Nation and provide ample opportunity for entry of this substance into ground waters.

NTA from detergents could possibly enter ground water both by infiltration through the soil mantle above the water table and discharge directly into the ground water. The first pathway would be operative in cases where waste waters are discharged to permeable soils appreciably above the water table, such as in properly designed and operating septic systems, waste lagoons, and related sewage spreading systems. The second pathway would be followed in the all too frequent situations where septic systems, lagoons, and similar waste disposal systems are connected directly to ground waters, and also in cases of direct artificial recharge of aquifers.

Both during infiltration through the soil mantle and upon entry to the ground-water environment below the water table, NTA would be subject to possible sorption by soil particles and microbial degradation. Also, since it is an exceptionally efficient chelating agent, NTA might also react with metals present in the soils to form soluble metal chelates. Therefore, answers to the following questions are needed in order to assess the probable impact on ground water of large scale use of NTA in detergents.

1. How will sorption affect the infiltration of

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[a] Prepared for the National Ground Water Quality Symposium, Denver, Colorado, August 25-27, 1971.

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NTA through soil profiles and its movement within ground-water aquifers?

2. To what extent will NTA be degraded during infiltration through unsaturated and saturated soils and within essentially anaerobic ground-water environments?

3. If NTA is degraded during infiltration through soil profiles or within ground-water environments, what will be the nature and fate of the degradation products?

4. To what extent will NTA affect the transport of metals into and through ground water?

This report describes a research project undertaken in an effort to provide answers to these questions. The project was part of a relatively short term but intensive effort by the Environmental Protection Agency to evaluate the environmental acceptability of NTA before its large scale use in detergents is begun, and research was therefore limited to a laboratory investigation consisting of three phases conducted more or less concurrently. The first phase of the investigation involved study of the sorption of NTA by typical sand, loam, and clay-loam soils. In the second phase, soil column studies were employed to investigate the possible degradation and effect on metals of NTA infiltrating through saturated and unsaturated soils. In the third phase of study, the possible degradation of NTA in an essentially anaerobic ground-water environment was investigated using simulated aquifers constructed in the laboratory from natural aquifer sand.

SORPTION STUDIES

Sorption of NTA by soils was investigated by laboratory sorption studies employing a sand, a loam, and a clay-loam soil in order to broadly span the various soil types which might be encountered in natural situations. The soils used, all of which were obtained in the vicinity of Ada, Oklahoma, were identified by the United States Department of Agriculture Soil Conservation Service soil surveys as Konawa loamy fine sand, Claremore loam, and Burleson clay loam.

Solutions of the trisodium salt of NTA (NTA Na_3) uniformly labeled with carbon-14 were utilized in the sorption studies as well as in the other phases of this investigation. Soils were placed in contact with various concentrations of ^{14}C-NTA Na_3 in Erlynmeyer flasks and the mixtures were agitated at 20°C until equilibrium was attained. Concentrations of NTA Na_3 in the solutions at equilibrium and quantities of NTA Na_3 sorbed by the soils in contact with these solutions were determined by liquid scintillation spectrometry. Sterile solutions and soils as well as aseptic techniques were employed throughout the sorption studies to eliminate the possibility of errors due to microbial degradation of NTA.

The data obtained for sorption of NTA on the soils utilized in this investigation were best described by means of the Freundlich adsorption isotherm, as shown in Figure 2. Greatest sorption was evidenced by the loam soil, with the sand being least effective. At an equilibrium concentration of 50 mg/l of NTA Na_3 in water, sorption values for the loam, clay-loam, and sand soils were 64, 28, and 8.7 μg NTA Na_3 per gram of soil, respectively. Analogous data at 5 mg/l NTA Na_3 were 10.2 μg/g, 3.5 μg/g, and 0.98 μg/g.

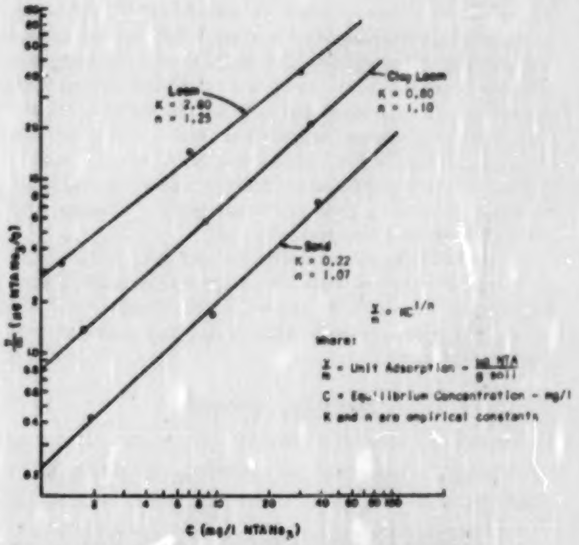

Fig. 2. NTA sorption; Freundlich isotherm at 20°C.

These data indicate that under some circumstances sorption of NTA by soils could considerably retard movement of this compound into ground water and within aquifers. Nevertheless, as an individual mechanism, sorption of NTA by soils does not appear to be sufficient to greatly reduce the potential pollution of ground waters by this compound over the course of its long-term usage as a detergent builder. However, by retarding the movement of NTA in soils and hence effectively increasing its residence time in regions of high microbial activity, sorption may play a significant secondary role in the removal of NTA from infiltrating waters by microbial degradation.

SOIL COLUMN STUDIES

Studies Employing Natural Soils

Initial soil column studies were concerned with the possible degradation of NTA during infiltration through unsaturated and saturated Konawa loamy fine sand, Claremore loam, and Burleson clay-loam soils and the effect of NTA on the metals native to these soils. The soils were packed into 4-inch O.D. × 4 feet borosilicate glass columns to produce columns of soil which were 3.75 inches in diameter and averaged 39 inches in height. Two columns of each soil type were prepared, with one being operated under unsaturated, or aerobic, conditions with the water table near the bottom of the column, and the other being operated under saturated, or essentially anaerobic, conditions by maintaining the water table near the surface of the soil. Loam and clay-loam columns are pictured in Figure 3.

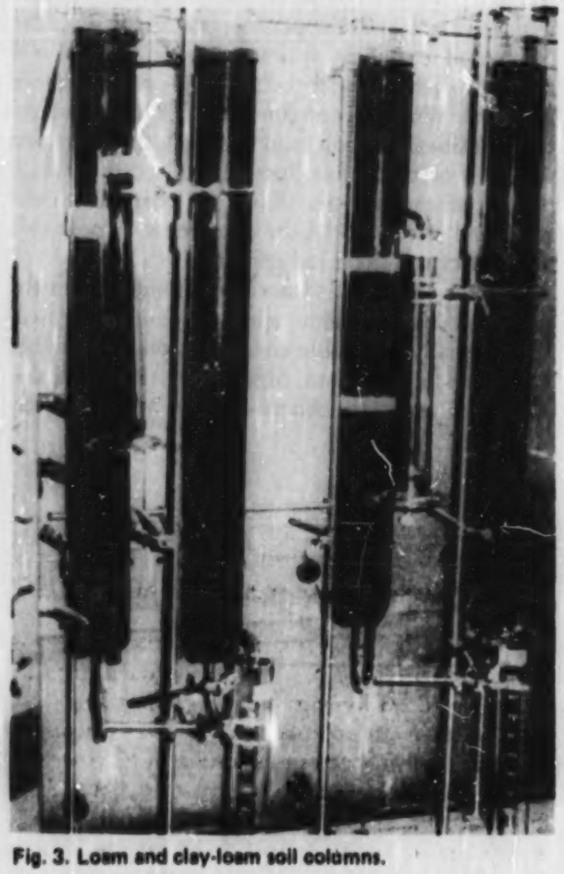

Fig. 3. Loam and clay-loam soil columns.

Columns were dosed daily for 58 days at a hydraulic loading of 2 gal/ft^2 (580 ml/day for each column) with a weak synthetic sewage prepared from the liquid diet food Sego, ^{14}C labeled NTA Na_3, and distilled water. The synthetic sewage contained approximately 50 mg/l both of BOD and NTA Na_3 and had a specific activity of 900 pCi/ml. Upon completion of the initial 58 days of operation, dosing of the soil columns was continued for 19 additional days with synthetic sewage containing no NTA in order to better observe the effect of NTA on the soil metals.

Column effluents were analyzed daily for NTA Na_3 by the automated zinc-zincon method (Thompson and Duthie, 1968) and for ^{14}C by liquid scintillation spectrometry. Selected effluents were also subjected to thin-layer chromatography and radioautography to detect intermediate organic degradation products of NTA. Effluents were examined initially by emission spectroscopy for evidence of metal increases. Those metals observed to increase significantly were then determined quantitatively by atomic absorption spectrophotometry, employing standard procedures (Federal Water Pollution Control Administration, 1969).

As shown by Figures 4 and 5, essentially no NTA was detected in effluents from the unsaturated loam and clay-loam columns at any time during the 77 days of operation, even though approximately 29 mg of NTA Na_3 were applied daily to each column. NTA was present in the effluent from the unsaturated sand column from the 2nd through the 9th day of operation, with a peak level near feed concentration occurring on the 5th day, but had virtually disappeared from this effluent by the 10th day and was not again detected as an effluent constituent (Figure 6). Significant quantities of ^{14}C not accountable as NTA were found in the effluents from all 3 columns during most of the period of operation, thus confirming the occurrence of NTA degradation in the columns. The early pres-

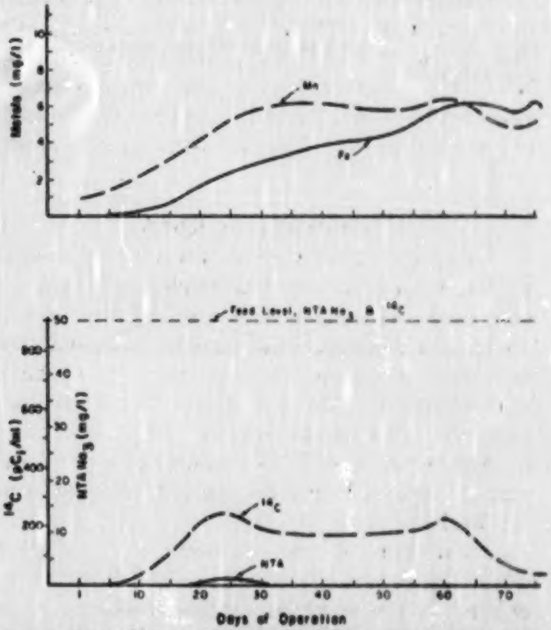

Fig. 4. NTA, ^{14}C, and metals in effluent from unsaturated loam column.

ence and subsequent disappearance of NTA in the sand column effluent undoubtedly reflected a short acclimation period required for establishment within the soil of a microbial population capable of degrading NTA. Because of the greater sorptive power of the loam and clay-loam soils, the movement of NTA in these columns was probably retarded sufficiently that acclimation and subsequent degradation occurred before any NTA traversed the lengths of these columns.

Thin-layer chromatography and radioautography studies revealed no organic degradation products of NTA in effluent samples from any of the unsaturated soil columns. Radioanalysis of gas released when effluent samples were acidified indicated that virtually all of the ^{14}C present in effluents from all 3 columns was incorporated in CO_2.

These data indicate that NTA infiltrating through unsaturated soil systems probably will undergo rapid and complete degradation, with the only products likely to enter ground waters as a result of such degradation being CO_2 and probably inorganic nitrogen compounds. The introduction of additional carbon and nitrogen into ground waters is certainly less than desirable, but the magnitude of the addition likely to result from the projected use of NTA in detergents is probably not sufficient for critical concern.

NTA and ^{14}C appeared in effluents from the sand and loam columns operated under saturated, or essentially anaerobic conditions on the 4th and 11th days of operation, respectively (Figures 7 and 8). After attaining concentrations near or some-

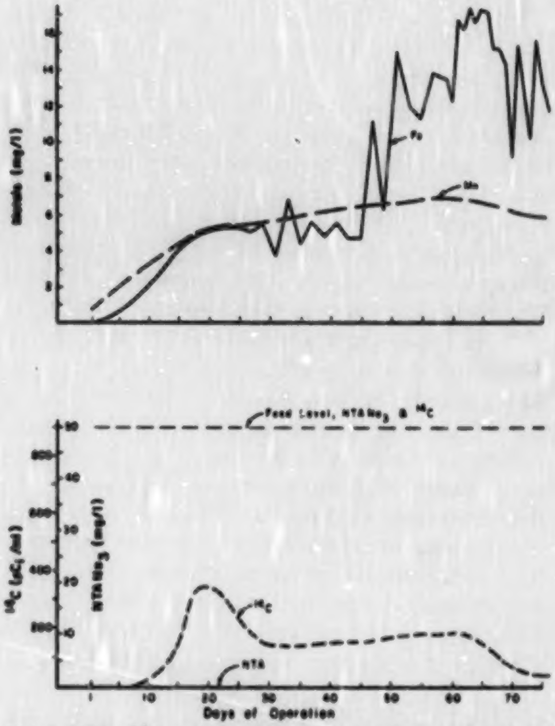

Fig. 5. NTA, ^{14}C, and metals in effluent from unsaturated clay-loam column.

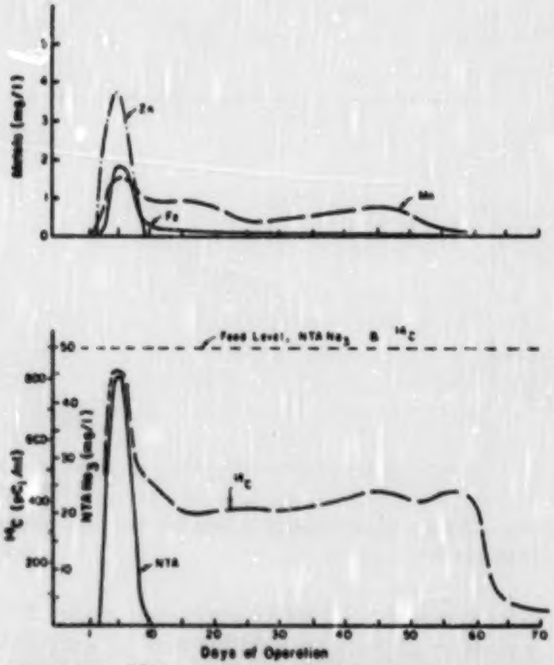

Fig. 6. NTA, ^{14}C, and metals in effluent from unsaturated sand column.

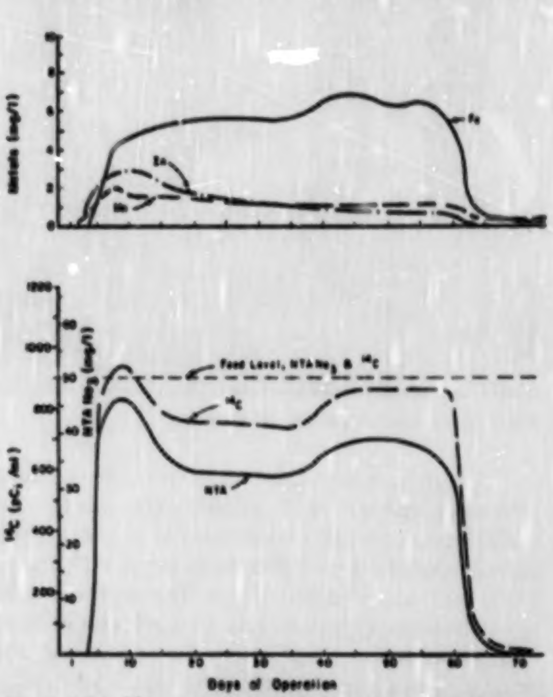

Fig. 7. NTA, ^{14}C, and metals in effluent from saturated sand column.

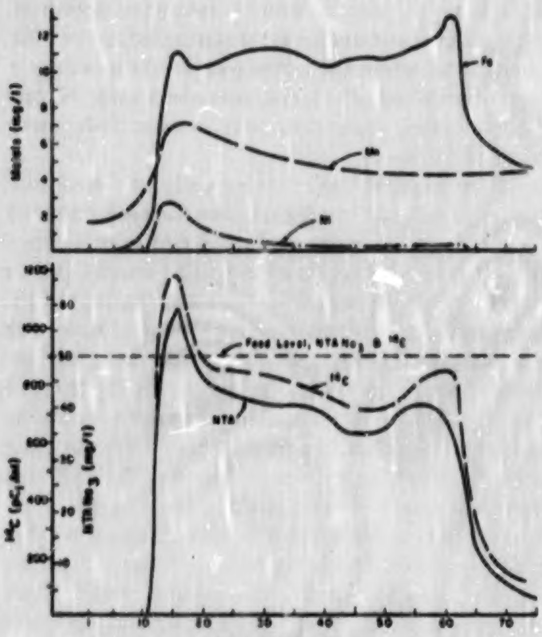

Fig. 8. NTA, ^{14}C, and metals in effluent from saturated loam column.

what exceeding the feed level (50 mg Na_3/l) during the early phases of column operation, NTA Na_3 in effluents from these columns remained within the range of 65-85 percent of feed levels until dosing with NTA Na_3 was terminated. Following initial peaks, ^{14}C levels in both effluents also decreased and were generally 80-95 percent of feed concentration for the remainder of the dosing period.

NTA and ^{14}C first appeared in the effluent from the saturated clay-loam column on the 7th day of operation, attained relatively low peaks on the 14th day, and then declined to minima on about the 29th day (Figure 9). This decline was attributed to aerobic degradation of NTA resulting from the presence of air in the capillary fringe of the column and possibly to the entrapment of air pockets in soil interstices throughout the column. After about the 30th day of operation, the saturated clay-loam column began performing in a manner similar to the other saturated columns, probably both as a result of intentional flooding of the capillary fringe of the column on the 29th day and depletion of oxygen in trapped interstitial air pockets.

The fact that NTA Na_3 and ^{14}C effluent concentrations were less than feed levels and ^{14}C effluent levels were equivalent to 2-10 mg/l more NTA Na_3 than actually appeared in column effluents during most of the operating period for both the saturated sand and loam columns and for the clay-loam column after the 30th day indicate that some degradation of NTA was occurring within these columns. It is not evident, however, if this degradation was truly anaerobic in nature, or if it was at least partially aerobic degradation which occurred in the capillary fringe regions of the columns and which was arrested by lack of oxygen as the feed solutions infiltrated deeper into the columns.

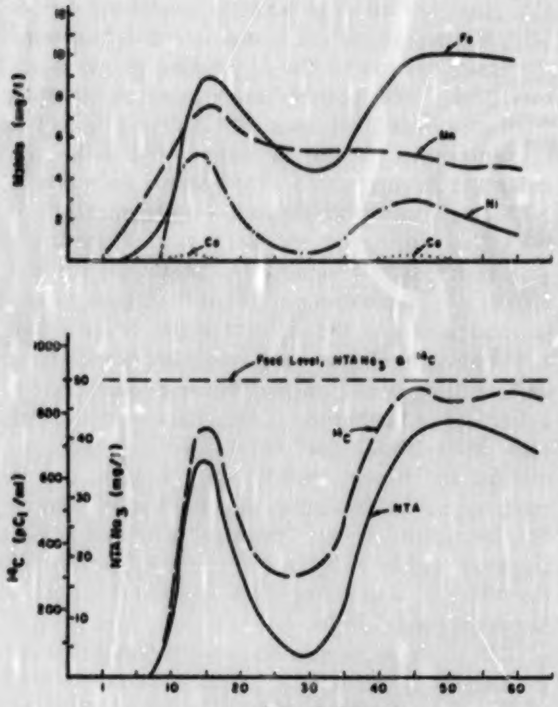

Fig. 9. NTA, ^{14}C, and metals in effluent from saturated clay-loam column.

Analysis of effluents from the saturated columns for $^{14}CO_2$ revealed that a major portion of the ^{14}C present in form other than NTA was incorporated in CO_2. Very small quantities of at least one organic degradation product of NTA were shown to be present in these effluents by thin-layer chromatography and radioautography, but the extremely low levels of the substance prevented its identification.

The data obtained in these studies with saturated soil columns show that NTA infiltrating through saturated soil systems, such as flooded septic tank percolation fields or under waste water lagoons, will likely undergo at most only slow degradation, and hence high proportions will probably reach ground water essentially unchanged. Some NTA degradation products could possibly be produced in saturated soils, but the quantities entering ground water would likely be extremely small.

As indicated in Figures 5-9, there were generally good correlations between concentrations of NTA Na_3 and of iron, zinc, nickel, cobalt (although the concentration of the latter element was never very high), and possibly manganese in effluents from various soil columns. The decreases in metals concentrations in the saturated sand and loam column effluents which accompanied decreases in NTA Na_3 concentrations following termination of NTA Na_3 dosing on the 58th day of operation appear particularly significant. Observation of the effects of termination of NTA dosing on metals concentrations in the effluent from the saturated clay-loam column was not possible because clogging and resulting poor flow performance precluded the collection of further meaningful data from this column after about the 60th day. However, the minima in effluent metals concentrations corresponding to the minimum in NTA Na_3 concentration occurring on the 29th day of operation provides significant additional information concerning the effect of infiltrating NTA on the metals in the saturated clay-loam soil.

Reasonable caution must be exercised in interpreting these metals data because of the lack of comparison data from control columns. Nevertheless, the results of these experiments indicate strongly that NTA which infiltrates through overlying soil without being degraded is likely to solubilize and transport into ground water metals native to the soils.

Studies Employing Sand Enriched with Metals

In order to further investigate the possible transport of metals into ground water by NTA, additional soil column studies were conducted employing columns prepared from Konawa loamy fine sand enriched with lead, zinc, chromium, cadmium, and mercury.

Six soil columns 3.75 inches in diameter and approximately 39 inches in depth were used. Two were prepared from sand enriched with the following natural ores: galena (PbS); sphalerite (ZnS); chromite ($Fe(CrO_2)_2$); greenockite (CdS); and cinnabar (HgS). The other 4 columns were packed from sand enriched with a synthetic sludge prepared by alkali precipitation of lead, cadmium, chromium, and zinc from a solution of their soluble salts, with subsequent drying and grinding of the precipitated sludge. Mercuric sulfide (cinnabar) was also added to the sludge-enriched sand as a source of mercury. The individual columns contained 5 g of each of the 5 metals, except that only 995 mg of chromium was present in each of the 2 sand-metal ores columns because the chromite ore contained only very low levels of this element.

Two of the columns containing synthetic sludge were operated under unsaturated, or aerobic, conditions, while the other pair of sludge-containing columns and the 2 columns containing the ores were operated under saturated, or essentially anaerobic, conditions.

The columns were dosed daily at a hydraulic loading of 2 gal/ft^2 (580 ml/day for each column). One column of each pair was dosed with 67 mg/l of ^{14}C labeled NTA Na_3 in distilled water (specific activity 920 pCi/ml), while the 2nd column of the pair served as a control and was dosed with distilled water only. Starting with the 56th and 53rd day of operation, respectively, for the columns dosed with NTA and the control columns, sufficient Sego to impart a BOD of 50 mg/l was added to the daily feed solutions. The columns were operated for a total of 92 days.

Effluents from columns dosed with NTA Na_3 were analyzed for NTA Na_3 and for radioactive carbon as in the initial soil column studies. Iron, manganese, lead, zinc, chromium, and cadmium were determined in effluents from all 6 columns by atomic absorption spectrophotometry, while mercury was determined by the flameless atomic absorption procedure (Federal Water Quality Administration, 1970). Data obtained for the columns dosed with NTA are presented in Figures 10-12.

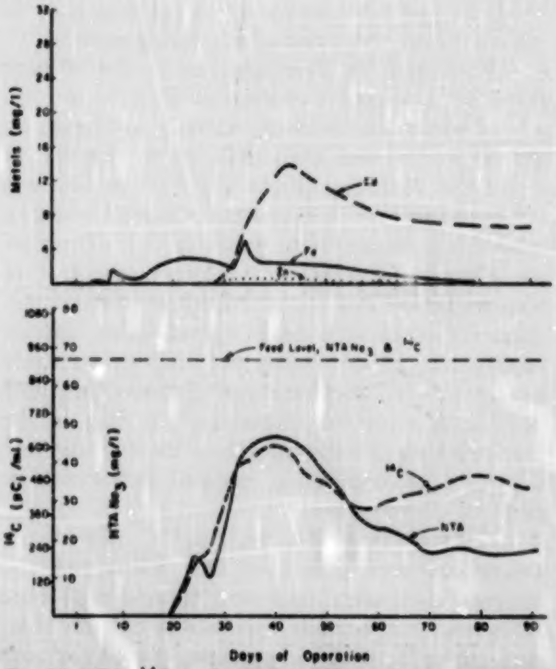

Fig. 10. NTA, ^{14}C, and metals in effluent from unsaturated sand-metals sludge column.

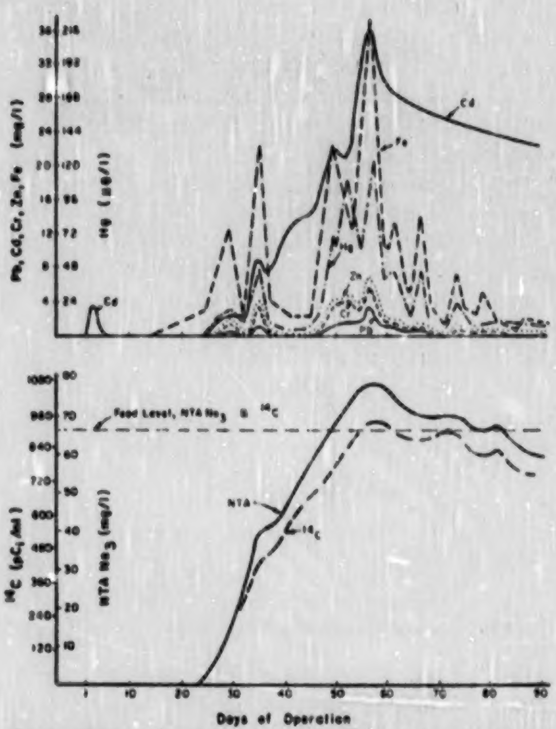

Fig. 11. NTA, ^{14}C, and metals in effluent from saturated sand-metals sludge column.

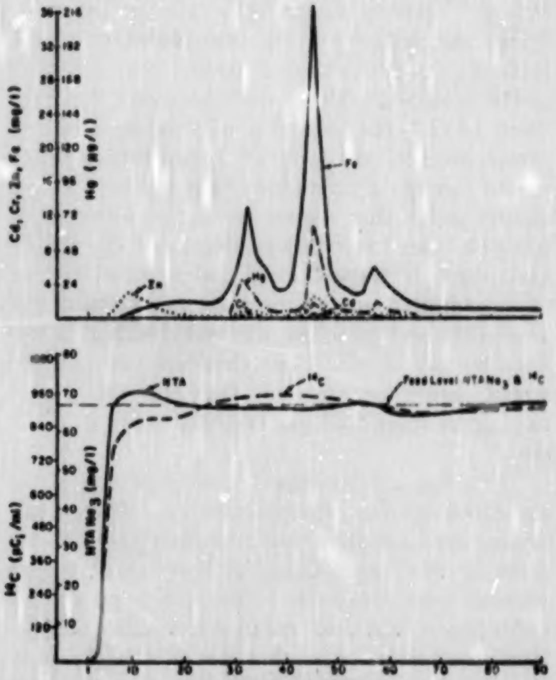

Fig. 12. NTA, ^{14}C, and metals in effluent from saturated sand-metal ores column.

NTA first appeared in the effluents from the unsaturated and saturated columns of sand enriched with metals sludge on the 19th and 22nd day of operation, respectively (Figures 10 and 11). NTA concentration in the unsaturated column effluent attained a maximum on the 39th day, and then declined to become relatively stable at about 25 percent of feed level after the 70th day. In the saturated column effluent NTA concentration reached a maximum on the 57th day and then slowly declined until termination of the experiment. NTA first appeared in the effluent from the saturated column of sand enriched with metal ores on the 3rd day of operation, attained a concentration near the feed level on the 7th day, and remained near feed level for the remaining 85 days of the study (Figure 12).

Comparison of these data with similar data obtained from the unsaturated and saturated sand columns in the initial soil column studies (Figures 6 and 7) reveals that the movement of NTA through sand enriched with metals sludge was very much slower than through sand alone, while NTA movement through sand enriched with metal ores was little different than movement of this compound through sand alone. Obviously, the metal hydroxides which principally constituted the metals sludge exerted some retarding effect on infiltrating NTA not manifested by the metal ores, which were mostly sulfides.

As Figure 10 shows, only about 75 percent of infiltrating NTA was degraded in the unsaturated sand-metals sludge column, while NTA was completely degraded, after a short acclimation period, during infiltration through the unsaturated column containing only sand in the initial soil column studies (Figure 6). This effect most likely was due to toxic effects of the heavy metals in the sludge which resulted in partial inhibition of microbial activity in the sand-metals sludge column.

The total quantities of metals eluted from the columns dosed with NTA were in every case manyfold greater than the quantities eluted from the corresponding control columns receiving no NTA.

As shown by Figures 10 and 11, cadmium levels were very high in effluents from both the unsaturated and saturated sand-metals sludge columns, attaining maxima of 14 mg/l and 36 mg/l, respectively, at the same time that peak NTA concentrations occurred. Iron and zinc were also present in the effluent from the unsaturated column, and high levels of iron, which had not been added to the metals sludge, appeared intermittently in the saturated column effluent. In addition, lesser quantities of zinc, chromium, lead, and mercury occurred in the latter effluent during the period that

NTA was present, with peak concentrations generally appearing in synchrony with iron peaks. As with the saturated sand-metals sludge column, iron was intermittently present in high concentrations in the effluent from the saturated sand-metal ores column (Figure 12), together with lesser quantities of zinc, chromium, cadmium, and mercury.

Throughout the period of operation, concentrations of the metals mentioned above were either very small or below detectable levels in effluents from the control columns.

Solubilization and transport of metals from the soil by NTA appears to be the only explanation for the significantly greater quantities of metals eluted from the experimental columns than from the control columns. The experimental and control column pairs were prepared from identical quantities of the same enriched soils and were operated by identical procedures except for the addition of NTA to the feed for the experimental columns. There were essentially no differences in pH values and redox potentials in effluents from experimental and control columns.

The data obtained in these experiments leave little doubt that infiltration of water containing NTA through saturated soils containing heavy metals could result in solubilization and subsequent transport of such metals into ground waters. These studies also indicate that infiltration of water containing NTA through unsaturated soils containing high levels of heavy metals could result in both NTA and metals entering the underlying ground water because of metals toxicity and the resulting inhibition of microbial degradation of NTA. The extent and nature of metals solubilization and transport by infiltrating NTA in a specific natural situation will obviously depend on such variables as the quantities of various metals in the soil, the anionic species with which the metals are associated in the soil matrix, the concentration of NTA in the infiltrating solution, and the relative stabilities of the various metal-NTA complexes under conditions prevailing in the particular soil system of concern.

Over-all, the soil column studies described above indicate some potential for pollution of ground water by metals as a result of the use of NTA in detergents. Accurate evaluation of the actual extent and seriousness of this potential will likely require thorough evaluation of the complex factors affecting the formation of chelates by NTA and metals in soils, including metals native to the soils and those deposited by waste disposal.

SIMULATED AQUIFER STUDIES

In order to investigate the possible degradation of NTA in the essentially anaerobic groundwater environment, model aquifers simulating as nearly as possible conditions prevailing in a natural aquifer were constructed in the laboratory. Figure 13 shows details of the simulated aquifer design.

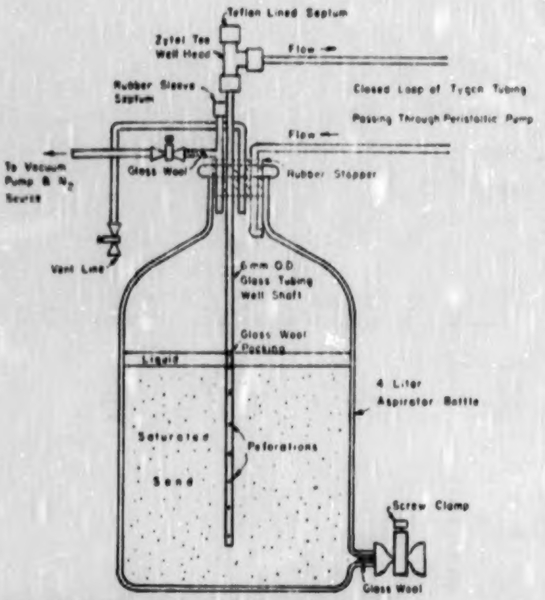

Fig. 13. Details of simulated aquifer design.

Each laboratory aquifer was constructed from a 4 l aspirator bottle containing 3 l of natural aquifer sand. A 6 mm O.D. borosilicate glass tube with perforations placed in a spiral arrangement below the surface of the sand served as a well shaft. This tube was packed loosely with glass wool and was topped with a ¼-inch Swagelok Zytel tee "well head." The side arm of this tee was connected to a closed loop of Tygon tubing which passed through a peristaltic pump and back to the aquifer unit. This system permitted water to be pumped from the saturated depths of the aquifer sand through the well head and returned via the closed tubing system to the aquifer unit. The upper arm of the well head tee was sealed with a Teflon-lined rubber septum through which the pumped stream could be sampled. Ports for evacuation, gassing, venting, and gas sampling were also provided.

Natural aquifer sand for construction of the simulated aquifers was obtained near Byars, Oklahoma, from a shallow aquifer underlying the floodplain of the South Canadian River. Aseptic procedures were employed to the extent possible in collection of the sand and in construction of simulated aquifers in order that the microbial population of the models might approach that of the natural aquifer. Three simulated aquifers were constructed, with one being sterilized by autoclaving after loading of the sand to serve as a control. Initial charging of the simulated aquifers was achieved by first removing most of the water native to the aquifer sand by application of vacuum at the bottom outlets of the aspirator bottles and then allowing sterile solutions of NTA Na_3 in distilled water to flow into the evacuated units. The NTA in the feed solutions for the sterile control aquifer and one of the other units, designated Simulated Aquifer Number 2, contained carbon-14, while the NTA in the feed for the third unit, designated Simulated Aquifer Number 1, contained no radioactive isotope. Conditions of very low oxygen tension were created within each aquifer unit by twice thoroughly evacuating and refilling with nitrogen gas.

The simulated aquifers were operated in a darkened room at 20°C for 265 days. For the final 122 days they were operated under a blanket of nitrogen to further preclude the possibility of oxygen entering the units. The aquifers were recharged with NTA after 52, 143, and 209 days of operation by aseptic addition of small volumes of relatively concentrated sterile NTA Na_3 solutions through the tops of the units. Because the volumes of water in the aquifers and the quantities of NTA Na_3 sorbed on aquifer sand could only be estimated, the concentrations of NTA Na_3 actually present in the aquifer waters immediately after the initial charging and subsequent rechargings of these units varied from 30-55 mg/l. Sufficient Sego to impart a BOD of 60-90 mg/l to the water in each aquifer was included in the third recharge in order that the effect of an extraneous carbon source on NTA degradation might be observed.

The aquifer units were pumped occasionally for a few hours to simulate movement of ground water and to maintain as much uniformity as possible within the units, particularly after recharging. Units were always pumped for a short period immediately before sampling in order to obtain representative samples from the depths of the aquifers. Samples were obtained at 3-7 day intervals by withdrawing required quantities of liquid through the well head septums by means of sterile syringes while the units were being pumped. These samples were analyzed for NTA Na_3 and for ^{14}C as previously described. Selected samples were also subjected to thin-layer chromatography and radioautography, and the composition of the gas in each unit was determined by gas chromatography each time a liquid sample was obtained.

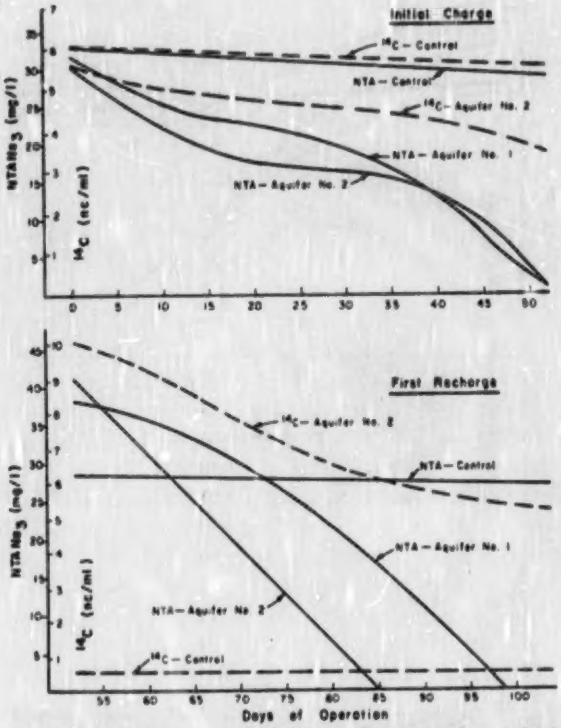

Fig. 14. Degradation of NTA in simulated aquifers; initial charge and first recharge.

As shown by Figure 14, significant microbial degradation of NTA occurred in the experimental simulated aquifers during the initial 52-day period of operation. Beginning concentrations of 30-32 mg NTA Na_3/l in the aqueous phases of both Aquifer Number 2, which contained ^{14}C-NTA, and Aquifer Number 1, which contained only non-labeled NTA, decreased to essentially zero during this period, while NTA Na_3 in the sterile control aquifer decreased only from approximately 33 mg/l to 29 mg/l. In the periods following the first and second rechargings of the simulated aquifers, similar degradation of NTA occurred in the experimental units, with the over-all rates being somewhat higher than in the initial period of operation (Figures 14 and 15).

Gas samples taken from the aquifer systems were found to contain low levels (usually less than 0.2 percent) of oxygen at various times during the initial period of operation, but essentially no oxygen was noted in such samples at any time after the first recharging. Gas analyses also revealed the production of methane and low levels of carbon dioxide in both experimental aquifers, with no production of either gas in the control aquifer. The methane produced in Simulated Aquifer Number 2, which contained ^{14}C-NTA, was found to be radioactive, thus confirming it as a degradation product of NTA. This would appear to show beyond reasonable doubt that the degradation of NTA in the simulated aquifers was truly anaerobic.

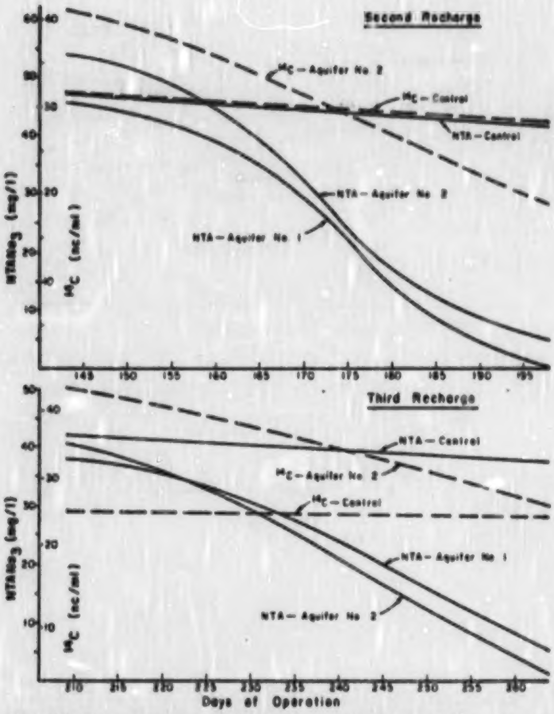

Fig. 15. Degradation of NTA in simulated aquifers; second and third recharges.

Thin-layer chromatography and radioautography gave limited evidence for the presence in Simulated Aquifer Number 2 during maximum degradation of NTA of an intermediate organic degradation product with chromatographic properties very similar to NTA. Time limitations precluded extensive study of this substance, and the possibility exists that it was a chromatographic anomaly, produced by the effect on NTA of salts or other substances in the sample solutions.

A large proportion of the ^{14}C introduced into Aquifer Number 2 with each NTA charge remained in the aqueous phase of the aquifer after essentially all of the NTA had disappeared (Figures 14 and 15). This ^{14}C was necessarily a component of degradation products of NTA, but hardly any of it could be accounted for on radioautograms of aquifer samples obtained after NTA had disappeared from the units. Although a portion of this ^{14}C was undoubtedly present in the form of carbon dioxide and methane, it appears that other volatile degradation products, which would have been lost during sampling and chromatography and hence would not have been detected by radioautography, may have been present in the aqueous phase of the aquifer after all of the NTA had been degraded. Obviously, the pathways, intermediates, and final products of degradation of NTA under anaerobic conditions need further elucidation.

Degradation of NTA proceeded at slightly reduced rates in both of the experimental aquifers after the third recharging, which included Sego as a carbon source in addition to NTA (Figure 15). The magnitude of these rate decreases were relatively small, however, and there is no certainty that they were attributable to the extraneous carbon source since products of microbial metabolism which had accumulated in the aquifers during the 210 days of operation prior to the third recharge could also have caused some decrease in NTA degradation. It should be noted that addition of an extraneous carbon source to an aquifer with the initial charge of NTA, before the microbes present in the aquifer have adapted to degrade NTA, could produce a quite different effect than observed here.

Over-all, the data obtained in the simulated aquifer studies indicate that NTA entering an essentially anaerobic ground-water environment will likely undergo degradation, with methane, carbon dioxide, and possibly other volatile compounds being the probable final products of such degradation. This phenomenon could be quite important in retarding the development of high levels of NTA in aquifers receiving waste waters which contain this substance and in decontamination of aquifers which might become polluted by NTA. It should be noted, however, that the sand employed for construction of the simulated aquifers in these studies was obtained from a very shallow natural aquifer which probably contained a numerous and active population of anaerobic microorganisms because of periodic infusion with water of relatively high organic content. It is probable that anaerobic microbial populations in many natural aquifers, particularly deep aquifers, would be much less numerous and active; hence, the degradation of NTA, or at least the initiation of such degradation, would likely occur much more slowly in such aquifers than was observed in simulated aquifers during these studies.

CONCLUSIONS

The investigations described above permit the following conclusions concerning the potential impact of NTA on ground water.

1. Sorption of NTA by some types of soils may considerably slow the initial movement of this compound into and through ground waters. However, sorption of NTA by soils does not appear to be sufficient to prevent or appreciably decrease the pollution of ground waters by this compound over the course of its long-term usage as a detergent builder.

2. NTA infiltrating through unsaturated soils, as in properly operating septic tank percolation

fields, will probably undergo rapid and complete degradation. Only inorganic nitrogen compounds and carbonates are likely to enter ground water as the result of such degradation. Introduction of these substances into ground waters is not desirable, but the quantities introduced as a result of NTA use in detergents are not likely to be sufficient to create critical pollution problems.

3. The degradation of NTA infiltrating through unsaturated soils which contain high levels of heavy metals, such as those receiving wastes from metals plating operations, may be partially inhibited as a result of toxicity of the metals to soil microorganisms; hence, some NTA may enter ground water under such circumstances.

4. NTA infiltrating through saturated soil systems, as in flooded septic tank percolation fields and under some waste water lagoons, will likely undergo only limited degradation; hence, a significant portion will enter underlying ground water, possibly accompanied by small quantities of organic degradation products of NTA.

5. NTA which reaches the water table will likely undergo slow degradation in the essentially anaerobic ground-water environment. The final products of such degradation will probably include carbon dioxide and methane, and possibly other organic compounds of low molecular weight and relatively high volatility. Unknown intermediate products of NTA degradation may also be present in an aquifer when NTA is being actively degraded.

6. NTA that infiltrates through overlying soil into ground water without being degraded may solubilize and transport into the ground water such metals as iron, zinc, chromium, lead, cadmium, and mercury which may be present in the soil. Situations where NTA might infiltrate through soils receiving wastes containing high levels of toxic heavy metals, such as metal plating wastes, would appear to entail considerable potential for metals contamination of underlying ground waters. However, comprehensive evaluation of the potential threat to ground-water quality posed by solubilization and transport of metals in soils by infiltrating NTA will require further elucidation of the factors controlling formation of NTA-metals chelates in soils.

7. Even in the most favorable circumstances, use of NTA as a detergent builder is likely to result in some increases in nitrogen and probably carbon in ground waters. Phosphates in waste waters do not readily move into or through ground waters because of strong sorption in soils. Hence, in comparison to phosphates the use of NTA in detergents would likely result in at least a limited adverse impact on ground water.

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